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PROGRESS REPORT 3
TO
THE OFFICE OF PROBLEM ANALYSIS
APPLIED SCIENCE AND RESEARCH APPLICATIONS
NATIONAL SCIENCE FOUNDATION

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Assessment of a Semi-Closed, Renewable Resource-Based Aquaculture System

MAY 20, 1979

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Assessment of a Semi-Closed, Renewable Resource-Based Aquaculture System

from
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MAY 20, 1979

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TABLE OF CONTENTS

Page

I. SUMMARY OF THE REPORT 1

II. EXPERIMENT #1: TESTING SURFACE AREA AND AERATION 4

- A. DESCRIPTION 4
- B. WATER CHEMISTRY METHODS AND DISCUSSION 10
- C. RESULTS - FISH GROWTH AND WATER CHEMISTRY COMPARISONS .. 12
- D. NOTES ON SYSTEM DESIGN 18
- E. SUMMARY OF EXPERIMENT #1 19

III. EXPERIMENT #2: TESTING NITROGEN INPUT TYPES AND RATES 20

- A. DESCRIPTION 20
- B. MEASUREMENT METHODS AND MATERIALS 22
- C. RESULTS 27
- D. DISCUSSION OF RESULTS 37

IV. EXPERIMENT #3: FISH MONOCULTURE UNDER DIFFERENT AERATION RATES 54

- A. DESCRIPTION 54
- B. WATER CHEMISTRY METHODS AND MATERIALS 56
- C. RESULTS AND DISCUSSION 57

V. EXPERIMENT #4: COMPARATIVE GROWTH EVALUATION: MONOSEX HYBRID TILAPIA VS. *Sarotheradon aureus* MIXED SEX POPULATION 71

- A. DESCRIPTION 71
- B. RESULTS 72
- C. DISCUSSION 72
- D. SUMMARY OF EXPERIMENT #4 73

VI. ENHANCING THE COMPUTER SYSTEM FOR DATA ACQUISITION AND ANALYSIS 74

VII. MATHEMATICAL MODELS 77

- A. INTRODUCTION 77
- B. STATISTICS PROGRAMS 78
- C. RELATIVE PROPORTIONS IN ACID/BASE PAIRS 83
- D. DATA CONVERSION PROGRAMS 87
- E. MODELS WITH IMMEDIATE IMPLICATIONS FOR SOLAR-ALGAE POND MANAGEMENT 100

TABLE OF CONTENTS (cont.)

Page

VIII. FUTURE COURSE OF RESEARCH 120

A. MODELING 120
B. EXPERIMENTAL DESIGNS AND SEQUENCE FOR YEAR 3 120

IX. BIBLIOGRAPHY 125

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I. SUMMARY OF THE REPORT

Many subtleties of aquatic ecology and fish productivity in solar-algae ponds* have been revealed over the past year by the routine application of a battery of chemical tests combined with continuous electronic monitoring. The resulting time series data provides the base upon which to build a model of the flows of energy and nutrients through the ponds. Five basic points can be made:

1. Fish feeding rates and types affect fish growth.

Under good water conditions tilapia incorporate half of the nitrogen in the commercial feeds tested. With adequate feed, growth rates exceed 50 pounds per pond per year. Algae in a pond, supplied with fertilizer, can supply the maintenance energy needed by two kilograms of tilapia, but cannot foster significant growth.

2. The ecosystem absorbs nutrients potentially toxic to fish.

This year's research has documented a central premise of solar-algae pond fish culture: algae absorb large amounts of toxic fish wastes during active algal growth.

3. Feeding rates affect water quality.

At moderate feeding rates the fish and plankton can assimilate most nitrogen, preventing the accumulation of dissolved inorganic nitrogen compounds (ammonia, nitrite and nitrate). To maintain good water quality, the feeding rate must be within the ecosystem's capacity to absorb residual toxic nutrients.

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*Translucent fiberglass cylinders roughly five feet in diameter and height, holding approximately 630 gallons of water.

4. Water quality affects fish growth.

Two water quality conditions have been observed that harm fish growth: a) high pH during strong algae growth, combined with high feeding rates, can cause ammonia to accumulate in its toxic un-ionized form, and b) heavy decomposition from high feeding rates and/or the accumulation of dead algal cells leads to low pH and oxygen, and high ionized ammonia, nitrite, nitrate, phosphate and carbon dioxide.

5. Solar-algae ponds conserve energy.

The energy costs of producing fish protein in solar-algae ponds compare favorably to the most efficient methods of providing animal protein (i.e., Israeli pond fish polyculture and egg production). In solar-heated buildings, the ponds ultimately capture five times more energy than was used in manufacturing the fiberglass silos.

In the following sections we detail the results from four long-term productivity experiments conducted in the past year, and discuss their implications. Experiment #2 (pp. 20-55) represents the heart of the report, where a wide range of feeding regimes, pond ecologies and fish growth rates are documented and discussed. Improvements in the computer system are then traced, bringing us to a description of the computer models developed to synthesize and draw meaning from the data. Finally, the future course of research is charted: a comprehensive model of fish growth and water quality is outlined, and the experiments to be conducted over the next year are described.

The appendices include the articles published or submitted for publication over the past six months, written by members of the research team.

II. EXPERIMENT #1: TESTING SURFACE AREA AND AERATION

Primary System Evaluation: Fish Culture in Solar-Algae Ponds Comparing Nocturnal vs. Continual Aeration and Simple Pond Design vs. Ponds with Internal Substrates
(April 23 to July 11, 1978)

A. DESCRIPTION

1. Overview:

This experiment was two-fold in purpose. It was used to determine which key factors are necessary to monitor for optimal fish growth conditions, and to evaluate the impact of aeration and internal substrates upon fish productivity. Twelve solar-algae ponds in outdoor courtyards adjacent to the Cape Cod Ark were used in this experiment. This first experimental set was intentionally kept simple; for example, the ponds were stand alone rather than linked. A single fish species, Sarotheradon aureus, was cultured to avoid interspecific effects and the more subtle questions of niche matching and system optimization.

The stocking density reflected a middle-of-the-road approach. They were below the highest culture density used in these ponds in the past, yet high enough to be considered relevant in both economic and biological terms.

In the present experiment we evaluated algal and fish productivity, the biological composition of the ponds and nutrient and gaseous phenomena against two variables to unlock significant information from the systems. Half of the ponds had interior habitats; half had continuous aeration as against 12-hour nocturnal aeration regimes in the remainder. In summary, the first experiment involved a monocrop fish culture tested against the chemical and biological variables of interior habitats and aeration.

2. Physical Design:

a. Basic Components: Pond Walls and Covers

Sheets of fiberglass-reinforced polyester bonded with fiberglass or epoxy resins can be formed into a water tight translucent cylinder. A second covering of the same flexible material creates a calm 1 cm wide air space that retards conductive and convective heat loss. The ponds thus constructed are quite durable, and have a life expectancy of 20 to 30 years. Kalwall Corporation, Manchester, New Hampshire, markets the materials in this area. In other regions of the country similar materials are available from other manufacturers.

The inside diameter of the ponds used in these experiments may vary from 1.41 to 1.49 meters. The walls are 1.53 meters high and the water column is kept at 1.45 ± 0.02 meters deep containing approximately 2,300 liters.

b. Pond Location

The ponds are located both inside the Cape Cod Ark and in adjacent reflective courtyards to the east and west of that building. Ponds A-F are in the west courtyard standing in unconnected couplets. Ponds G-N are in the east courtyard also standing in couplets. In this experiment and the subsequent ones to be described, the solar-algae ponds will be referred to as Pond plus the letter of its specific location. The ponds inside the Ark are referred to numerically with ponds listed from 1 to 14.

c. Pond Weatherization

During winter the indoor ponds are covered with a cone-shaped lid made from the same fiberglass material to retard heat loss and evaporation. During the colder months outdoors, the ponds are covered with a circular piece of clear acrylic (1 cm thick) thermalpane material with a flap opening made of the same material. This product, Acrylite SDP (R) is distributed by CY/RO industries in Wayne, New Jersey. These tops are attached to the ponds with tape, allowing removal during warm months.

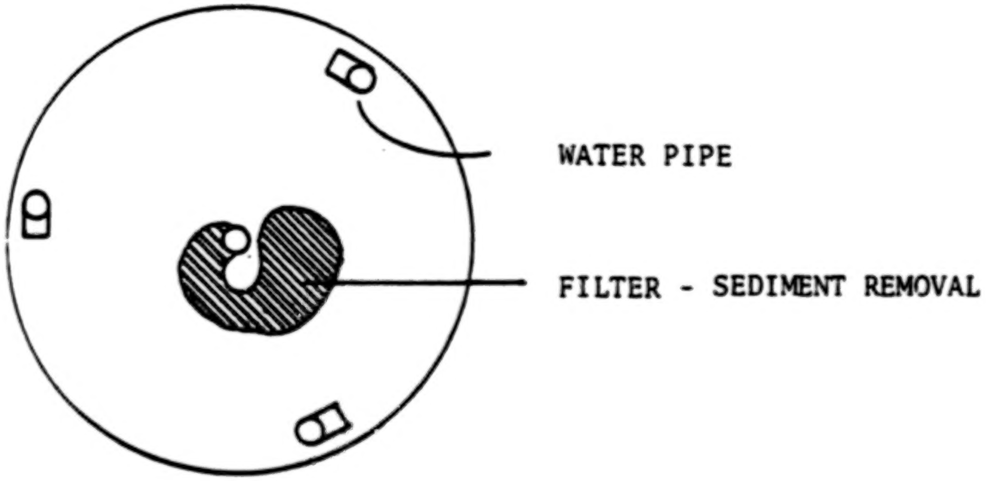
d. Sediment Removal

High photosynthetic rates and external feeding rates generate large amounts of dead algal cells and fish feces that accumulate on the bottom and impose a heavy biological oxygen demand on the water column. Unless these sediments are removed, anoxia results.

In the past, sediments have been siphoned or actively pumped off the bottom as often as once a week and as infrequently as once every two months. Unfortunately, the process consumes much time, and requires the replacement of 20% of the water volume.

An alternative sediment removal system was used in this set of experiments. Vertical pipes along the sides of the ponds have air lines within that pump water upward. Elbows at the top direct the water in a circular motion, which moves sediments to a central pipe where they are drawn up into a nylon stocking filter. Unlike siphoning, the internal filters require no replacement of water (Figure 1).

Figure 1: Top View of Solar-Algae Pond with Internal Filter:



e. Aeration

A central 1/3 horsepower dry air pump aerates all of the ponds via 3/4" plastic pipe. It is manufactured by the Condé Milking Machine Company in Wayne, New Jersey.

3. Fish Species and Biomass:

The single species used, Blue Tilapia or Sarotheradon aureus, is a herbivorous species with which we have had considerable experience.

Each pond was stocked with an equivalent fish biomass (approximately 850 grams) per pond. The fish ranged in size, and therefore the ponds had different population densities.

4. Feeding:

The fish were fed supplemental feeds at a level typical of intensive fish culture. Daily feeding levels varied from 0 to 15% of the fish body weight. Feeding was based on the projected weight of the fish and on pond environmental conditions. All systems were fed at the same rate. They were fed Blue Seal Rabbit Chow five days per week and Strike Trout Chow one day per week. The rabbit chow is primarily composed of alfalfa which was readily ingested by the fish. The trout chow was given to the fish for its balanced amino acid and vitamin content.

5. Experimental Variables:

a. Variable 1: Surface Area

The translucent solar-algae ponds do not normally have an internal structure apart from piping for aeration and air lifting of water. It was hypothesized that through adding a fine-mesh internal habitat extending nearly the full depth of the water column would increase in available pond niches and in the variety of indigenous food organisms. This has been demonstrated in natural ecosystems with the use of artificial habitats (Lim et al., 1976). We also wanted to determine if an internal substrate would stabilize the pond ecosystems and/or alter other aspects of its water chemistry and productivity.

b. Variable 2: Aeration

Nocturnal aeration was used to prevent anoxia when fish were kept at high densities. It also aids in nutrient and sediment redistribution.

Continuous aeration, energetically twice as costly, was to be evaluated to determine whether fish productivity was significantly improved. The expected advantages included 1) distributing light and nutrients more evenly among the algae, and 2) the addition of atmospheric CO_2 during daylight hours, preventing excessively high pH.

c. Experimental Design Summary

A total of 12 ponds were used in the experiment. The combination of two factors, aeration and internal habitats, creates a two-by-two Latin square (Figure 2). Three ponds represent each of the four combinations. One pond of each trio, or four ponds in all, were intensively monitored.

Figure 2: The 2 x 2 Matrix of Factors Tested in Present Experiment:

	NOCTURNAL AERATION	CONTINUAL AERATION
INTERNAL HABITAT	PONDS J,K,L	PONDS C,F,H
NO INTERNAL HABITAT	PONDS I,L,N	PONDS D,E,G

d. A Note on the Statistics of Three Replicates

A decision had to be made between one or two variables, more variables implying fewer replicates. Since the underlying variables of aeration and substrate were felt to be of possible real significance to future designs and modeling, we opted for both variables and fewer replicates. This decision was made with some temerity. Accidental systems failure in a number of ponds could reduce the amount of statistically valid information.

The "Student's -t" is used to test hypotheses where the standard deviation must be calculated from experimental values. The smaller the sample population, the greater the uncertainty about the width of the true standard deviation, and thus the greater the value of Student's -t. Student's -t for 95% certainty is 1.65 for an infinite number of samples (ponds in our case) and 2.92 for 2 degrees of freedom (or three replicate ponds).

B. WATER CHEMISTRY METHODS AND DISCUSSION

This experiment was used to evaluate the best techniques necessary for accurate determinations of the pond water quality. The experiment was in progress when the need for a broader water chemical analysis was realized. This included a spectrophotometric analysis of nitrogenous and phosphorous compounds. Nevertheless, some pertinent information was obtained using La Motte water test kits, and this led to improved management, sampling methods, and monitoring techniques for later experimental procedures.

In summary, the ponds were found to have high CO_2 concentrations from direct measurements with an Orion CO_2 probe and a Corning pH meter in May, 1978. Calculations from low pH and high alkalinity measurements supported this finding. Low ammonia concentrations during this period indicated that algal assimilation or nitrifying bacteria metabolism adequately used this fish waste. However, the presence of H_2S was detected by smell during early morning sampling, indicating anaerobic conditions. This was most likely due to detrital build-up on the bottom of the ponds.

Toward the end of this investigation, ammonia was found in concentrations as high as 6 mg/l. At the same time, the pH was also measured in a range low enough to cause the ammonia to be in its ionized nontoxic form (NH_4^+). These findings suggest that aeration and photosynthesis was not sufficiently high per unit volume to prevent the buildup of these nutrient wastes. As a result improved aeration efficiency and periodic 20% dilution practices was considered to maintain healthy water quality.

Using this same experiment a stratification analysis of several water chemistry parameters was undertaken. These measurements provided a contrast between the internal chemical conditions of nocturnal and continuous aerated ponds. The results from this evaluation are described in the article entitled, "Sunlight Patterns Without, Chemistry Patterns Within" found in Appendix I. This evaluation also provided the information for future sampling locations. From this, all continuous monitoring probes and water sample retrievals were taken from a spot in the center of the ponds, approximately 70 cm from the surface. This position was found to be a midpoint between the extremes of water quality stratification. The sampling was facilitated through the use of a siphon from this defined spatial area.

C. RESULTS - FISH GROWTH AND WATER CHEMISTRY COMPARISONS

From the fish growth and daily chemical spot check data of the experiment, the impact of the different pond treatments was found to be significant. The following Latin square representations are a compilation of average fish growth per day for each trio of similar ponds, and the deviation in water chemistry of the trio from the average for all 12 ponds.

Figure 3: Fish Growth (gms/day):

A:

	Habitat	No Habitat
Continuous Aeration	38.0	27.5
Nocturnal Aeration	19.0	35.0

Figure 3 (cont.):

DEVIATION FROM AVERAGE
(Spot Check Data, 33 pts. in time)

OXYGEN (mg/l):

		Habitat	No Habitat
B:	Continuous Aeration	0.26	-0.55
	Nocturnal Aeration	-0.24	0.51

SECCHI DISK (cm):

		Habitat	No Habitat
C:	Continuous Aeration	0.75	-0.02
	Nocturnal Aeration	-1.13	0.36

pH:

		Habitat	No Habitat
D:	Continuous Aeration	-0.17	-0.26
	Nocturnal Aeration	0.26	0.17

All of the water chemistry measurements for this experimental period were taken from pond water near the surface of the pond. The internal habitats were submerged more than 30 cm from the surface sample area. The upper regions of the pond usually have the most active photosynthetic activity. The readings were taken in mid-morning.

From the calculations and measurements listed in Figure 3, several relationships from the differing pond treatments are evident. Figures 3B and 3C demonstrate the relationship between Secchi disk and dissolved oxygen measurements. The Secchi disk measures photosynthetic depth in the pond. It appears that most of the turbidity in the upper regions of the pond is composed of live algal cells. The longer the Secchi disk reading the less the turbidity or number of algal cells. With the longer readings, there were lower concentrations of dissolved oxygen in the water. This appears to be true for the ponds under both aeration schemes.

In regard to fish growth, the most direct correlation to those factors described is with the measured dissolved oxygen concentrations. It appears that the ponds with the highest measured concentration of this gas also had a corresponding higher growth rate.

Figure 4: Deviation from Average:

		OXYGEN DATA, SHIFT IN DYNAMICS (mg/l)		
		Habitat	No Habitat	
A: May 25 - June 23 (17 Data Points)	Continuous Aeration	0.19	-0.98	-.40
	Nocturnal Aeration	0.45	0.34	.40
		.32	-.32	
B: June 24 - July 11 (16 Data Points)	Continuous Aeration	0.34	0.55	.45
	Nocturnal Aeration	-1.59	0.70	-.45
		-.63	.63	

Statistics Note: Standard error of the mean, based on six replicate means, is roughly .18 here.

In the first series of data points, oxygen levels were always in the teens on sunny afternoons. Although little can be said with 95% certainty (given the data's wide variability), the continuous aeration ponds appeared to have done more poorly than the nocturnal aeration ponds during daylight hours. This stands to reason, since the oxygen concentrations reached supersaturated levels on most days, and aeration would then tend to drive oxygen levels down to saturated levels.

In the second series of data points, the heavy BOD (Biological Oxygen Demand) held dissolved oxygen concentrations down even during the day. Concentrations seldom exceeded 10 mg/l. Under these heavy nutrient loading conditions, no aeration during the day resulted in lower oxygen levels, especially on cloudy days. Internal habitats also seem to strongly usurp available oxygen - probably through the creation of a substrate for trapping detritus and fostering dense bacterial populations, thus increasing the ratio of community respiration to photosynthesis. Note that in the early data set, the habitat seemed to slightly enhance daytime oxygen levels, perhaps by initially providing an algal substrate.

There appears to be a strong overall correlation between oxygen levels (actually the difference between one pond's dissolved oxygen and the average dissolved oxygen of all 12 ponds) and fish growth, as shown in Figure 5. One might first conjecture that low oxygen concentrations stress fish and, therefore, hinders growth. Causality might also flow the other way: stressed fish not eating food and leaving it to decompose

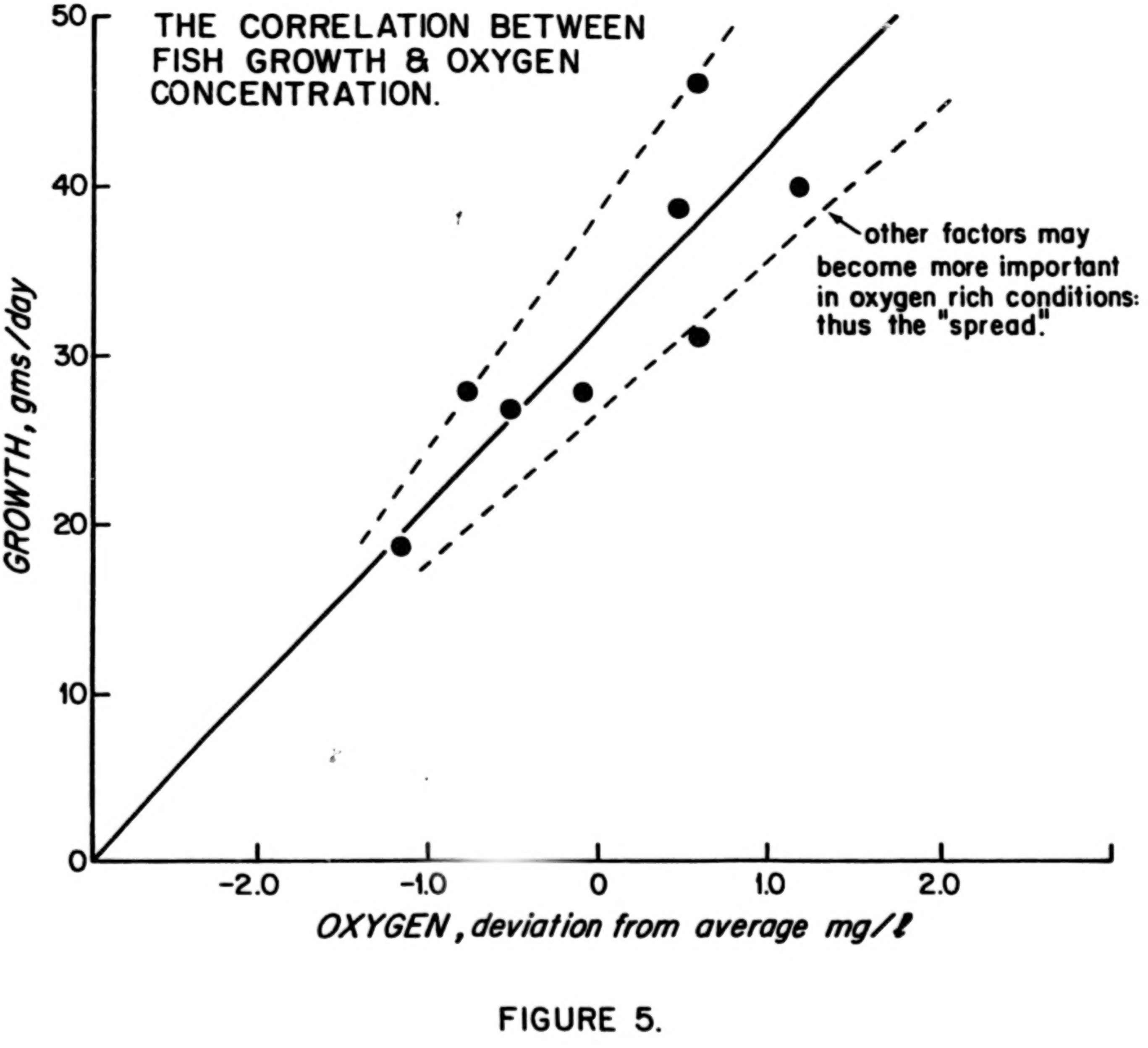

THE CORRELATION BETWEEN FISH GROWTH & OXYGEN CONCENTRATION.
other factors may become more important in oxygen rich conditions: thus the "spread."
GROWTH, gms/day
0
10
20
30
40
50
-2.0
-1.0
0
1.0
2.0
OXYGEN, deviation from average mg/l

FIGURE 5.

may increase decomposition and thus reduce oxygen. If food ingested by fish and then assimilated, respired or excreted exerts a lower BOD on the community than raw, uningested food, this second link exists. Its presence would complete a positive loop that would tend to amplify over time initially small differences between ponds.

D. NOTES ON SYSTEM DESIGN

1. Sediment Removal

The use of the nylon stocking filter and aeration/water movement tubes appeared to be somewhat of a liability as the experiment progressed and eutrophication ensued. The idea here was to eliminate the need for water exchange to maintain a more closed aquaculture. It rapidly became apparent that in order for the filter to be useful, it would have to be fine enough to remove the fine sediment material. This would therefore also result in the removal of the algal cells. Although the scheme was effective in capturing much of the fibrous wastes and larger fecal matter, the finer particulate wastes became increasingly more concentrated with time. This further increased the BOD. It was also noted that the continuous aeration pond filters collected more material, including some uneaten food.

The tube arrangement with the air diffusers within also appeared to be less efficient than freely suspended ones. The tubes' filter screens at the base also frequently became clogged. This aeration scheme was somewhat effective but the above problems plus the daily necessity of checking all the tubes for flow and removal of collected wastes required much daily maintenance time. This system design was discarded for the following experiments. A superior scheme is presently being sought.

2. Internal Habitats

The ideas behind the use of these plastic mesh substrates did not appear to render much advantage to the ponds productivity. Instead of providing a niche for zooplankton, they more or less became concentrators of detritus. They may be useful in ponds not as intensively fed as the ones in this experiment. Also, it has been surmised that the surface to volume ratio of the ponds alone is probably sufficient to provide the needed habitats for microorganisms. We have discontinued the use of these habitats until a more successful design is conceived.

E. SUMMARY OF EXPERIMENT #1

This experiment gave us insight toward the development of an effective means to evaluate the chemical nature of the ponds. It further assisted in the evaluation of a sediment removal scheme not previously tested. The impact and usefulness of internal habitats upon fish productivity of an independent solar-algae pond was also determined. Tilapia accepted and grew on a strictly vegetative feed not previously tested. This was the first intensive collection of data for the development of modeling strategies. Overall, this investigation provided baseline information for the evaluation of the experiments to follow.

III. EXPERIMENT #2: TESTING NITROGEN INPUT TYPES AND RATES

Monoculture Feeding Trials in Solar-Algae Ponds in Outdoor Reflective Courtyard (July 31 to November 13, 1978)

A. DESCRIPTION

1. Overview

This experiment involved four feeding treatments and 12 outdoor solar-algae ponds (labelled C through N). Its purpose was to assess the impact of these feeding treatments on pond ecology and fish growth. The appropriateness of these differing regimes was to be indicated by the presence or absence of deleterious concentrations of inorganic nitrogen compounds (ammonia, nitrite, nitrate); the levels of dissolved oxygen and carbon dioxide; and ultimately the rates of fish growth. Taken together they provided indices of loading, self-purifying and recycling rates within the phytoplankton-based aquatic ecosystems.

2. Physical Design

In this experiment, the sample ponds were used without any internal habitats. Aeration was supplied from air diffusers suspended freely in the ponds by clear plastic aquarium airlines. Three were supplied to each pond, and all the ponds were aerated.

A weekly 20% water exchange was done to assist in maintaining good water quality through dilution of accumulating wastes. The ponds were maintained without lids from the experiment's beginning on July 31, 1978, until September 13, 1978, when water temperatures were dropping well below optimal at night. The experiment continued with lids in place until termination on November 13, 1978.

3. Fish Species and Biomass

Each pond was stocked at the outset with 2,000 grams of the tilapia, *Sarotheradon aureus*.

4. Feeding Treatments

a. Fertilized Ecosystem Ponds C,D*,E

Human urine was added to these ponds at a nitrogen input rate approximately equal to that of the rabbit feed described below. The fish were not supplementally fed for the first five weeks of the trial. Later, in the experiment when water quality conditions deteriorated and measured fish growth was negligible, the urine inputs were terminated and replaced with comfrey.

b. Rabbit Feed at 3% Rate - Ponds I,J*,K

Rabbit feed (predominantly soy and alfalfa meal) with about half the protein content and one-third the cost of commercial fish feeds was fed at a rate of 3% of fish body weight daily except Sunday.

c. Trout Developer Feed at 3% Rate - Ponds L*,M,N

A commercial preparation of trout feed was fed at a rate of 3% fish body weight daily except Sunday.

d. Trout Developer Feed at 6% Rate - Ponds F,G,H*

The same feed as above was fed at the high rate of 6% daily except Sunday. Feeding at this rate had a feedback component. When un-ionized ammonia levels reached 1 mg/l, feeding stopped until the ecosystem regained equilibrium.

---

*Intensively monitored ponds.

B. MEASUREMENT METHODS AND MATERIALS

1. Water Chemistry

The mid-water sampling method resulting from Experiment #1's stratification analysis was used in the comprehensive water chemistry monitoring of the second experiment. The chemical parameters measured are listed in Table 1.

The electronically measured parameters were obtained every ten minutes and stored on the PDP-11 computer's flexible storage disks. Parameters allowing in situ measurement were taken during daily spot checks. The remaining parameters were measured in the chemistry laboratory at two-, or rarely, three-day intervals. Analytical procedures used for orthophosphate, nitrogen compounds, sulfate, and alkalinity are those described by the Bausch and Lomb Spectrokit (R) system for small water samples, modified in technique for greater accuracy. Other procedures followed techniques as described in Standard Methods. When experiments began, all colorimetric analysis was done with a Bausch and Lomb Spectronic 20 spectrophotometer* with precalibrated Bausch and Lomb Spectrokits (R). With the arrival of a Bausch and Lomb Spectronic 21 spectrophotometer, complete calibrations were made for this instrument.

Modifications of technique included the use of precision pipettes and meticulous cleaning and storage of all glassware. A warming reaction plate was designed and built to keep reaction temperatures at 25° ± 2°C. Experiments were conducted to assess variability of the

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*This instrument was loaned to us by Dr. Walter Rosen, then teaching at the University of Massachusetts, and now in the Toxic Substances Division of the E.P.A. Dr. Rosen is an adviser to the project.

Table 1. Physical and Chemical Parameters of Water Quality Program for Solar-Algae Ponds.

Parameter	Method	Sample Interval
Temperature	Thermocouple - electronic Precision mercury-filled thermometer	10 minutes Daily
pH	Specific ion probe - electronic	10 minutes and daily
dO	Specific ion probe - electronic Titration, Winkler Method	10 minutes and daily Occasional
Solar Radiation	Pyranometer - electronic	10 minutes
Alkalinity	Titration	2 days
Ca/Mg hardness	Titration	Occasional
$N-NH_4$	Nesslerization - spectrophotometric	2 days
$N-NO_2$	Diazotization - spectrophotometric	2 days
$N-NO_3$	Cadmium reduction - spectrophotometric and diazotization	2 days
PO_4	Ascorbic acid method - spectrophotometric	2 days
Turbidity	Spectrophotometric, .45 mμ filtration Secchi disk	2 days Daily
Sulfate	Barium chloride precipitation - turbidimetric	Occasional
Sulfide	Methylene blue method - spectrophotometric	Occasional

Spectrokit system with modifications for the nitrogen forms and orthophosphates. Results of these calibrations are presented in Table 2 for absorbances determined in half-inch test cuvettes with a Bausch and Lomb Spectronic 20 spectrophotometer. Thirteen millimeter matched test tube cuvettes were used and calibrated for the Spectronic 21 upon its arrival.

For each replicate calibration, fresh standard solutions were prepared from Orion and Bausch and Lomb prepackaged standard solutions or by direct dilution of analytical grade reagents. Error with each replicate reflected variability due to a loss of linear correlation of absorbance at high and low concentrations of the standard. For $N\text{-}NH_3$, $N\text{-}NO_2$, and $N\text{-}NO_3$, the lowest concentrations gave a low conversion factor, predicting higher concentrations than actually existed, and represented a limit to the absorption accuracy of the spectrophotometer read-out. At high standard concentrations, greater absorption values than predicted occurred and the conversion factors were biased low. For precision of our experiments, however, these error confidence intervals were acceptable, and adjustments for these reaction behaviors and actual pond sampling dilutions can be made with the data if greater accuracy is desired.

A copy of the water chemistry computation and recording sheet is included in Appendix II. Because of $N\text{-}NO_2$ interference with the $N\text{-}NO_3$ test, the difference between conversion factors for both standards provides the equation: $\text{true}(N\text{-}NO_3) = \text{measured}(N\text{-}NO_3) - 6.1(N\text{-}NO_2)$. Average conversion factors for 13 mm cuvettes and the Spectronic 21 instrument were also calibrated. Factors for $N\text{-}NH_3$, $N\text{-}NO_2$, $N\text{-}NO_3$ and PO_4

Table 2. Error Associated with Determinations of Nitrogen Forms and Orthophosphate in Standard Solutions.

Form	Standard Conc. Range Without Dilution	Replicate	n	Mean Conversion Factor, f, where $\alpha \cdot f$ = mg/l	Error	
					P = .05	P = .10
N-NH_3	.3 - 5.0 mg/l	1	5	4.78	5.2%	4.0%
	N-NH_3	2	5	4.77	4.5%	3.5%
		3	5	4.73	5.0%	3.8%
λ = 410 nm		Overall	15	4.76	.6%	.7%
N-NO_2	.1 - .4 mg/l	1	4	.294	4.3%	3.2%
	N-NO_2	2	3	.283	4.6%	3.1%
		3	3	.290	10.4%	7.0%
λ = 540 nm		Overall	10	.289	2.3%	1.9%
N-NO_3	1.0 - 4.0 mg/l	1	3	2.75	3.6%	2.4%
	N-NO_3	2	4	2.80	7.2%	5.3%
		3	4	2.88	14.3%	10.6%
λ = 540 nm		Overall	11	2.81	3.0%	2.5%
N-NO_3	.1 - .4 mg/l	1	3	4.31	11.9%	8.1%
	N-NO_2	2	3	4.82	11.2%	7.6%
		3	4	4.78	9.8%	7.3%
λ = 540 nm		Overall	10	4.64	8.0%	5.5%
PO_4	1.0 - 10.0 mg/l	1	4	16.87	2.4%	1.8%
	PO_4	2	4	17.46	5.9%	4.4%
		3	4	17.86	4.1%	3.0%
λ = 880 nm		Overall	12	17.20	4.1%	3.1%

were 4.71, 0.308, 3.02 and 18.21 respectively. Similar confidence limits for calibration and technique error were found for these conversion factors.

Water samples were analyzed immediately after collection from the experimental ponds. All samples were first filtered with a syringe-driven 25 mm .45 mμ Millipore (R) membrane filter system to remove algae and large bacterial populations. No contamination by nitrogen forms or orthophosphate was found in the use of this filtration method, and filtration of samples was necessary because plankton interfered with absorptance determination.

Various chemical interferences are associated with the methods and are outlined in Standard Methods and Spectrokit instructions. The extent to which these interferences might have occurred is not known. High concentrations of nitrogenous compounds at certain points during the experiment necessitated dilutions as great as 25 times. Dilutions can reduce the effect of interferences. Some interferences include a color change or precipitation not found in calibration standard determinations. When such inconsistencies occurred (which was seldom), further dilution was done until the expected color reaction resulted.

2. Algae Counting Methods

Algae were counted under a Unitron (R) phase microscope using an Improved Neubauer Nemacytometer manufactured by Hausser & Sons. Statistical analysis indicated that usually the true algae cell concentration was within 10-15% of the measured concentration with 95% certainty.

The range of uncertainty around the estimated densities of individual species was somewhat greater.

3. Fish Biomass Sampling Technique

The tilapia were distributed to ponds according to size classes; each size class had a 5 to 15 gram range. This allowed statistically significant sampling of subpopulations to determine average fish weight, and therefore (knowing the number of fish) total fish biomass.

The variability in individual fish weights indicated that the true average fish weight was within 10% of sample average (with 90% certainty) at the beginning of the experiment. At the end of the experiment the range had increased to 35%, since differences in individual growth rates caused the size classes to broaden.

C. RESULTS

1. Description

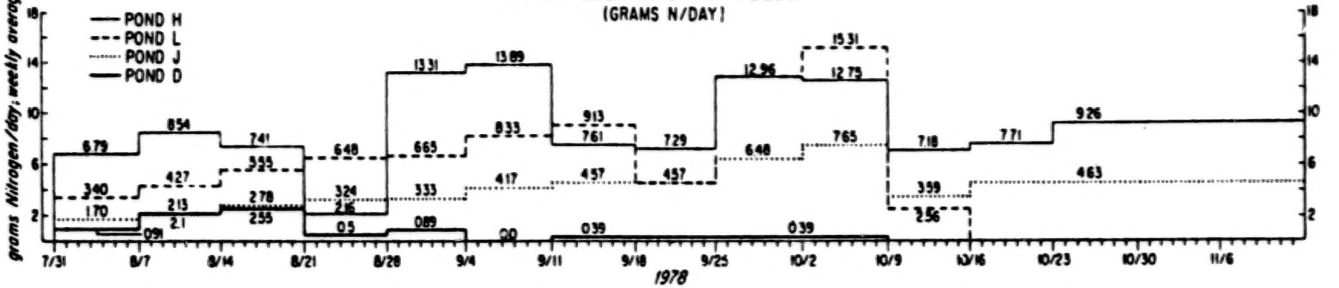
a. Algae (Figures 6 and 7)

i. Species Composition:

Throughout the second experiment green algae - as opposed to blue-green algae or diatoms - dominated in every pond. As shown in Figures 6B, 6C, 7A and 7B, the green algae *Ankistrodesmus falcatus* and *A. brauni*, prevalent initially, dropped out after the introduction of fish, suggesting *Ankistrodesmus* sp. are susceptible to fish predation. Different species replaced *Ankistrodesmus* in each pond, as expected since each pond shown experienced different kinds and rates

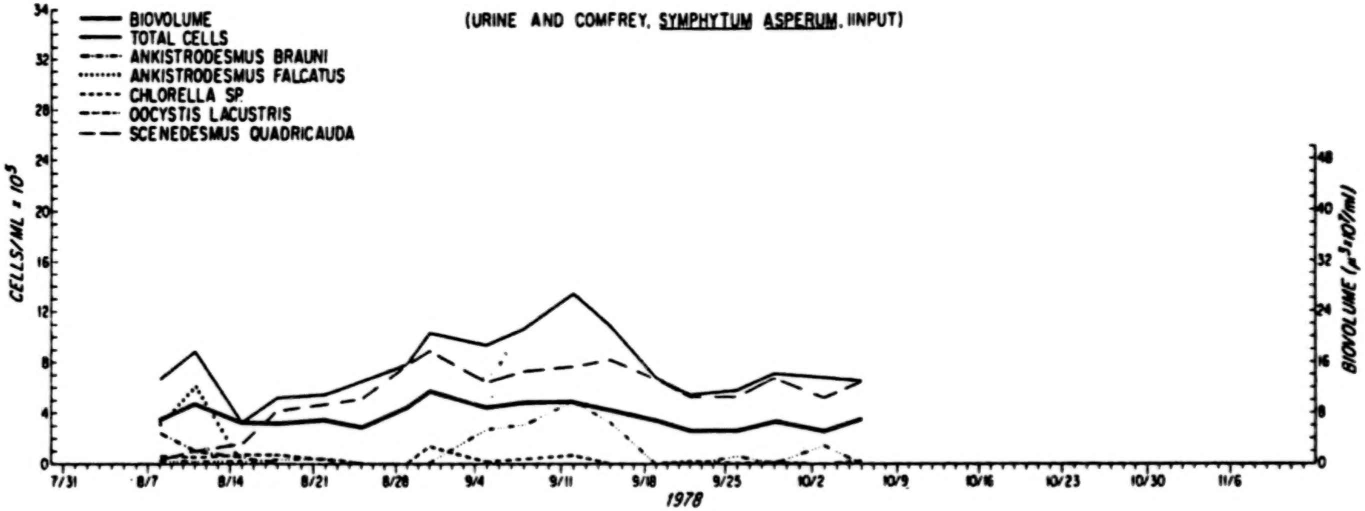
A. NITROGEN INPUT IN FEEDS

(GRAMS N/DAY)



B. ALGAL SUCCESSION IN POND D

(URINE AND COMFREY, SYMPHYTUM ASPERUM, INPUT)



C. ALGAL SUCCESSION IN POND J

(RABBIT CHOW, 3% FEEDING RATE)

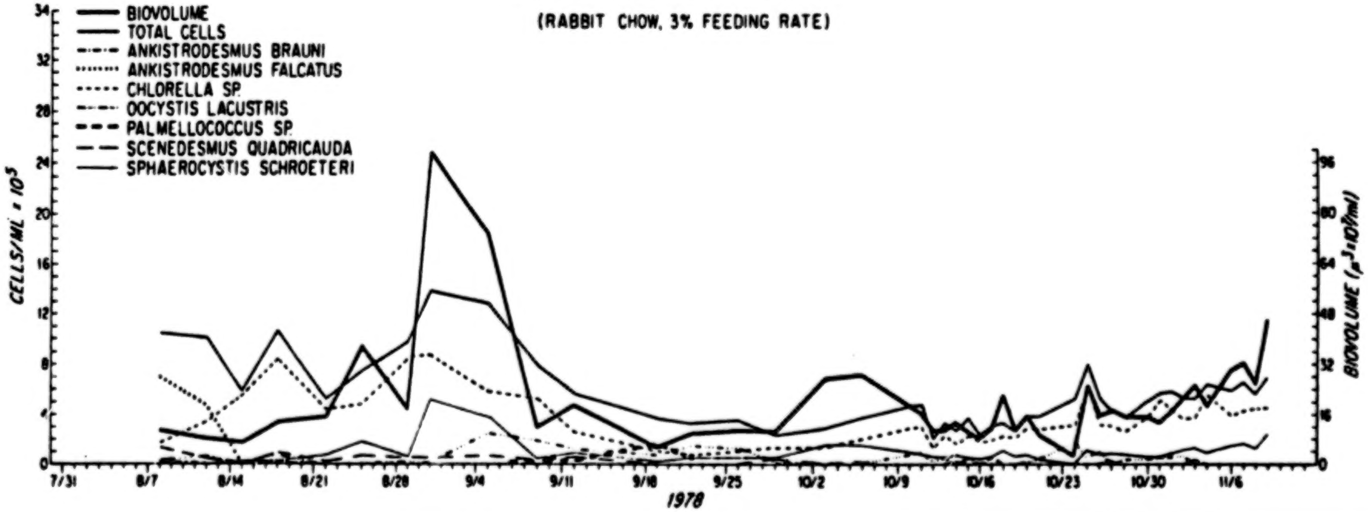
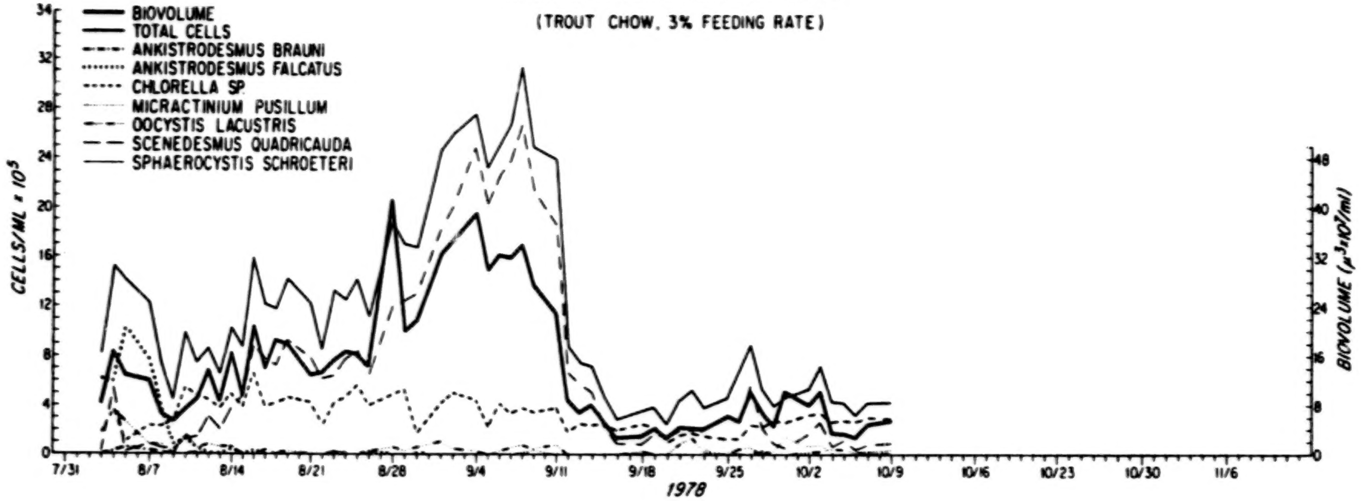


Figure 6

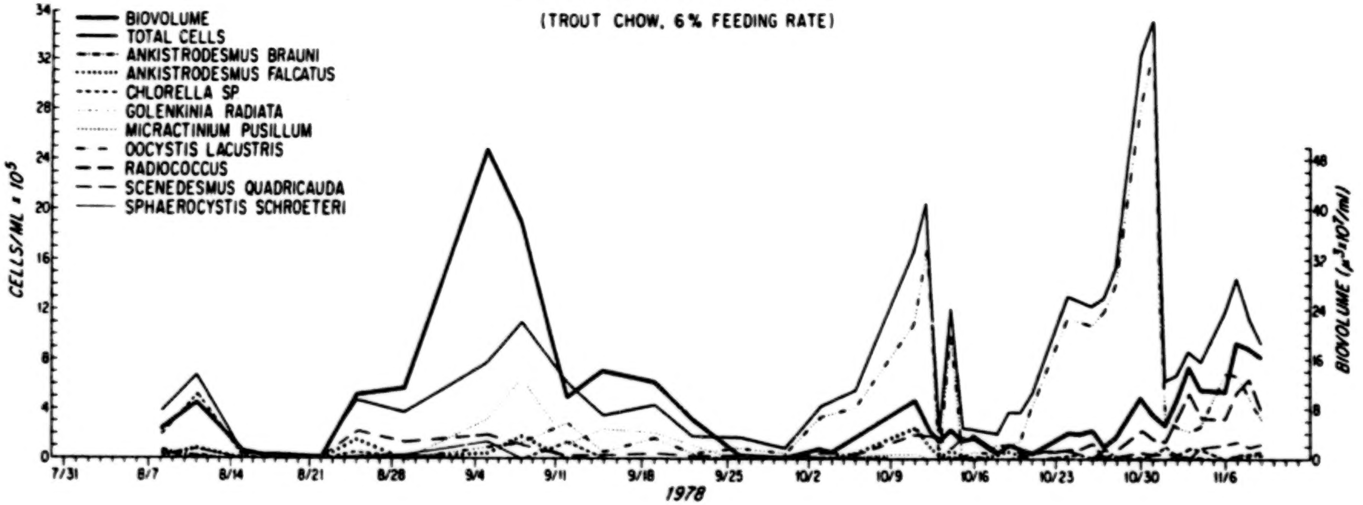
A. ALGAL SUCCESSION IN POND L

(TROUT CHOW, 3% FEEDING RATE)



B. ALGAL SUCCESSION IN POND H

(TROUT CHOW, 6% FEEDING RATE)



C. TOTAL DAILY HORIZONTAL SOLAR RADIATION

(CAL/CM²-DAY)

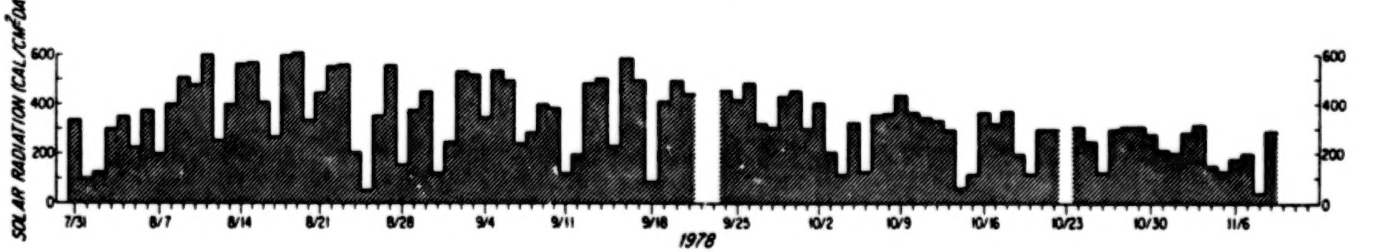


Figure 7

of nutrient loading (see Figure 6A). In Pond D, Scenedesmus quadricauda asserted dominance. Chlorella entered Pond J and persisted. In Pond L Scenedesmus proved the major species. In Pond H a variety of species played dominant roles at different times: Scenedesmus, Micractinium, Radiococcus and a Chlorella species less than 3 microns in diameter and mislabelled Oocystis lacustris on all the graphs.

ii. Biovolumes:

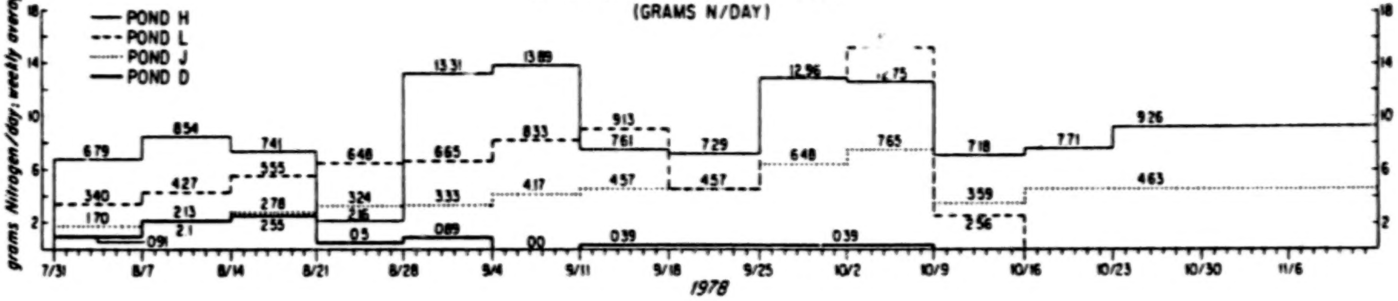
Looking at the overall biovolumes in Ponds J, L and H (Figures 6C, 7A and 7B), one realizes that on an aggregate volume basis the ponds undergo remarkably similar transformations. All of the ponds with dry feed inputs experienced a sharp rise followed by collapse roughly a month after the experiment's inception, although the species responsible for each peak differed: Sphaerocystis in Pond J, Scenedesmus in Pond L, and Micractinium in Pond H. According to systems theory, overshoot and collapse occurs where there is 1) exponential growth 2) toward an erodable limit (such as a depletable nutrient or an accumulating toxin), with 3) a delay in the response to the limit. The limit may be the build-up of detritus that blocks incoming light, or it may be the depletion of a trace micronutrient such as iron, magnesium or a vitamin. In all ponds the macronutrients carbon, nitrogen and phosphorous seem present in adequate amounts when the algae crashes occurred.

An interesting difference can be seen between ponds fed rabbit chow and trout chow. The rabbit chow treatment represented by Pond J exhibited a biovolume peak, and in fact biovolume levels throughout, that were roughly double those for the two trout chow regimes, Ponds L and H. Pond J also avoided the slow algae recovery experienced by Ponds L and H after the initial decline in Ankistrodesmus, and biovolume in Pond J peaked earlier. Note that the exception, the early sharp spike in Pond L, was based on a few sitings of very large Volvox colonies; that spike may have been much less pronounced than shown. All this suggests that rabbit chow either causes less turbidity, or contains a micronutrient absent in trout chow. In fact, rabbit chow contains large amounts of magnesium, the building block of chlorophyll, while trout chow does not.

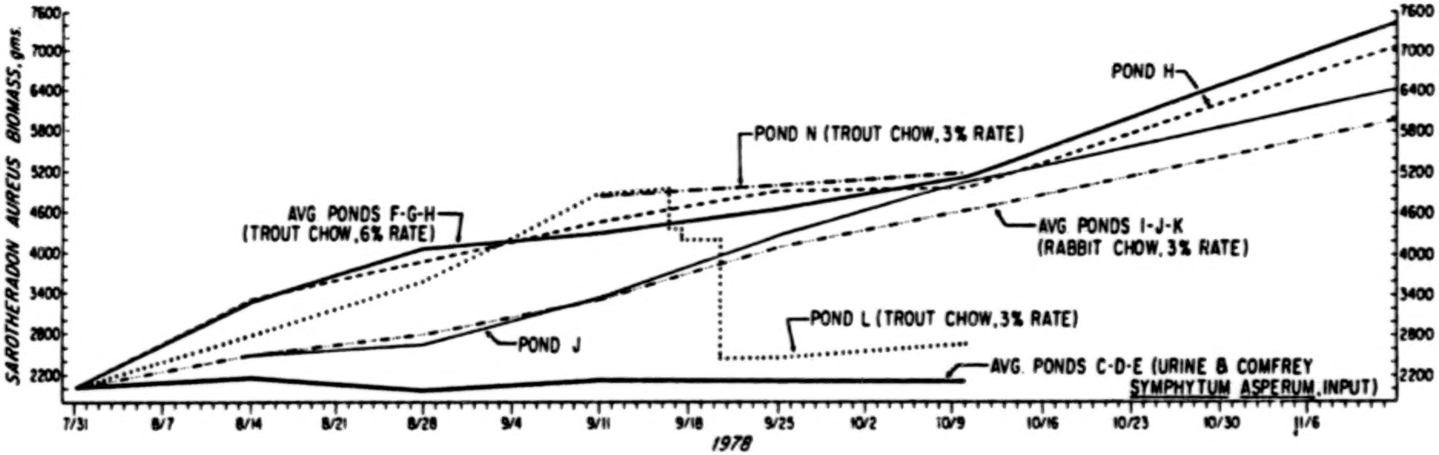
b. Water Chemistry and Fish Growth (Figures 8, 9 and 10)

The nitrogen input rates from feeding and fertilization (shown in Figure 8A) greatly influenced the concentrations of inorganic nitrogen compounds (see Figures 8C, 9A, 9B and 9C). The nitrogen in feeds had a direct effect on fish growth (Figure 8B), as well as an indirect effect through water quality. In Pond D nitrogen entered the pond in the form of urine, a fertilizer, rather than in the form of feeds. In that pond (Figure 8C), the rapid decomposition of urea to ammonia, combined with active algal photosynthesis that pushed pH above nine many afternoons, caused toxic un-ionized ammonia (NH_3) to climb above 3 mg/l (see the modeling section for the relationship between un-ionized ammonia and pH). Such concentrations are undoubtedly deleterious to tilapia growth (they would have killed trout or catfish). Urine inputs were discontinued after this time and replaced with comfrey leaves as a feed input.

A. NITROGEN INPUT IN FEEDS
(GRAMS N/DAY)



B. FISH GROWTH UNDER DIFFERENT EXPERIMENTAL REGIMES



C. NITROGEN COMPOUNDS, ORTHOPHOSPHATES & ALKALINITY (mg/ℓ) IN POND D
(URINE & COMFREY, SYMPHYTOM APERUM, INPUT)

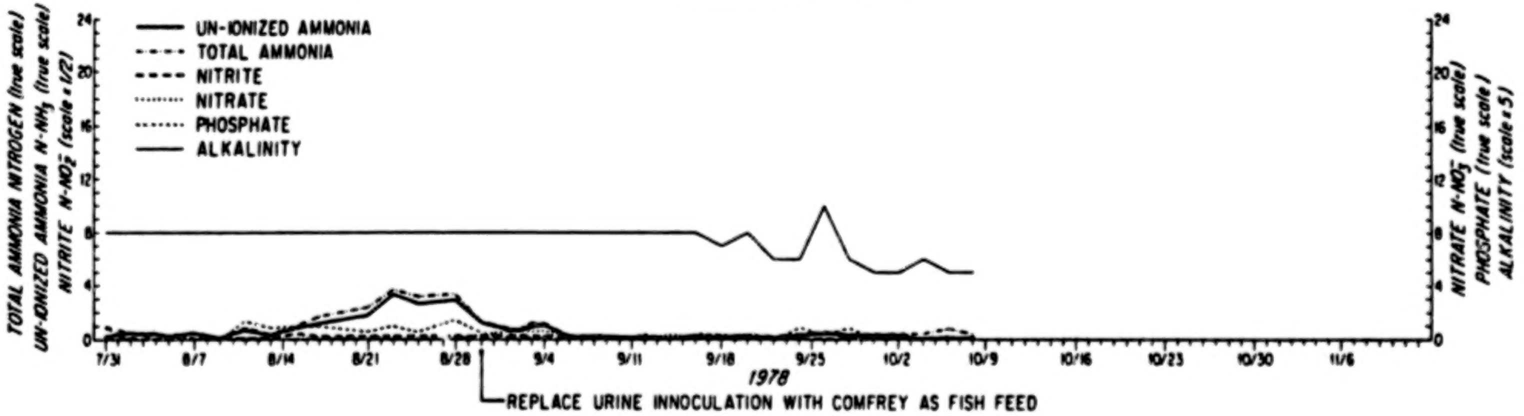
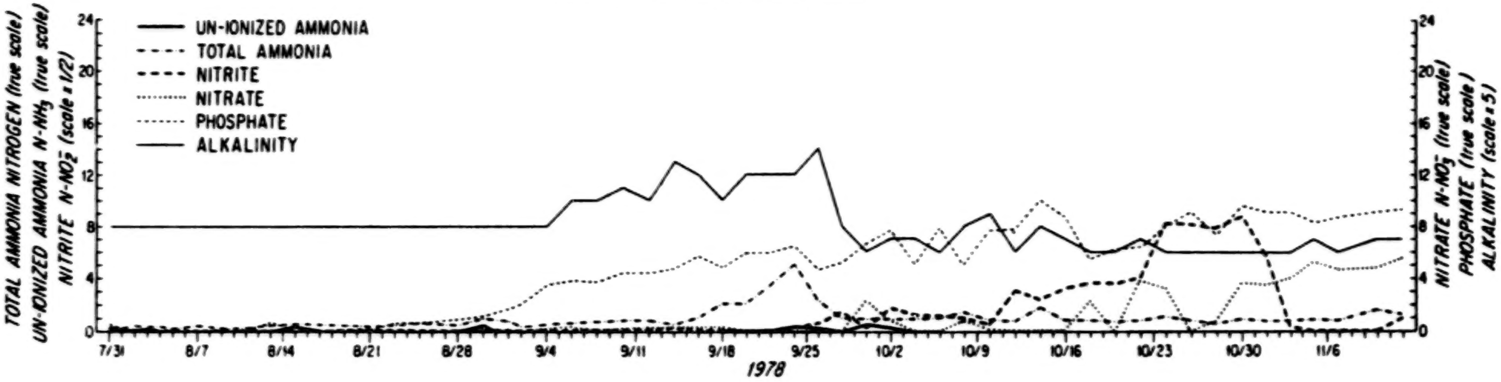
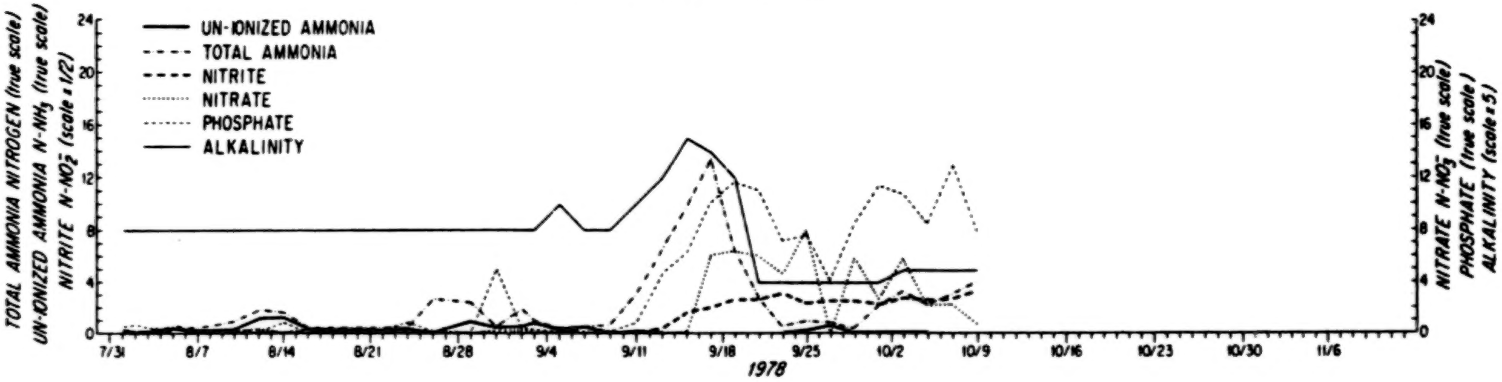


Figure 8

A. NITROGEN COMPOUNDS, ORTHOPHOSPHATES & ALKALINITY (mg/l) IN POND J
(RABBIT CHOW, 3% FEEDING RATE)



B. NITROGEN COMPOUNDS, ORTHOPHOSPHATES & ALKALINITY (mg/l) IN POND L
(TROUT CHOW, 3% FEEDING RATE)



C. NITROGEN COMPOUNDS, ORTHOPHOSPHATES & ALKALINITY (mg/l) IN POND H
(TROUT CHOW, 6% FEEDING RATE)

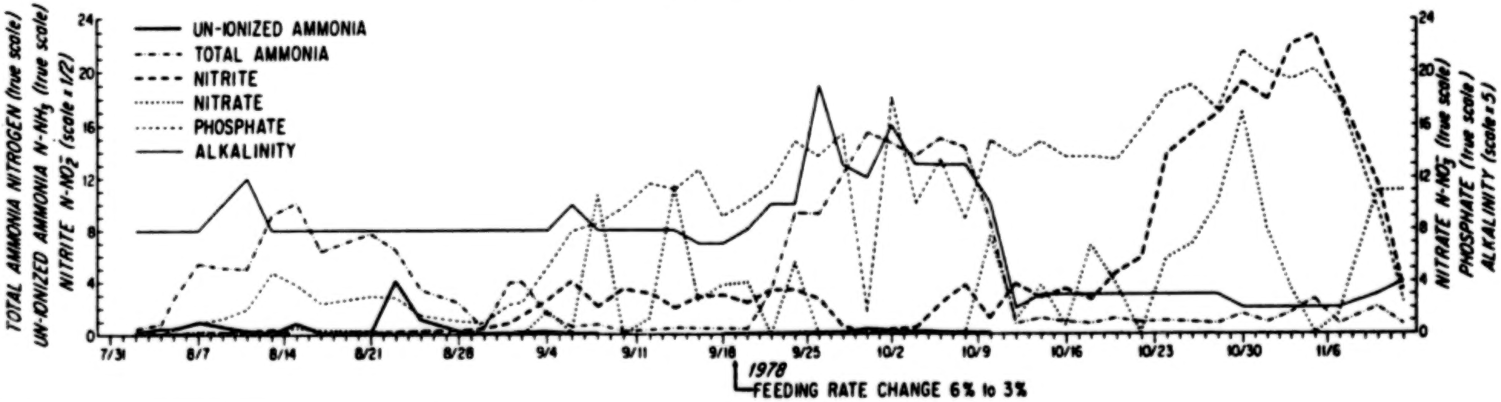
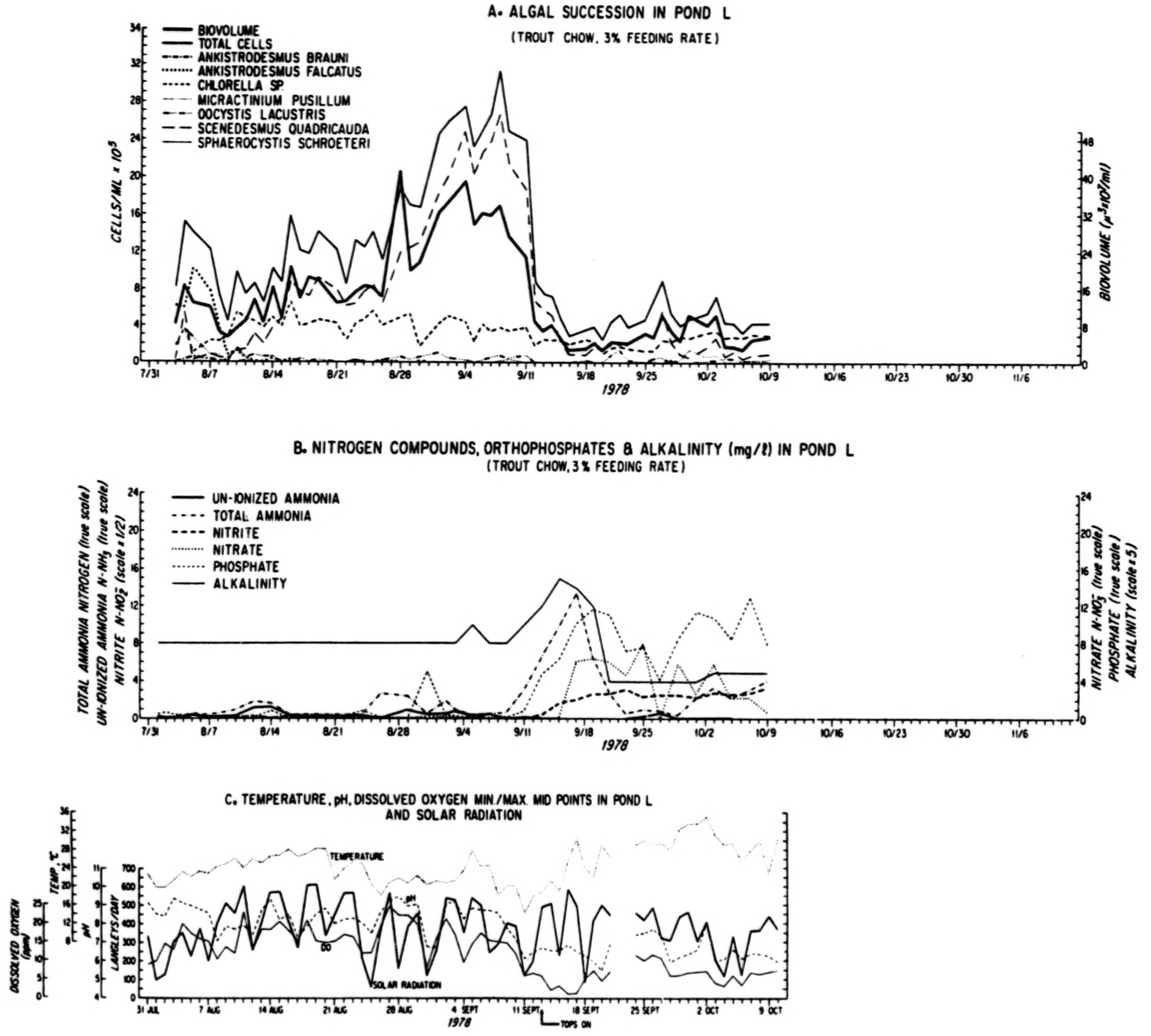


Figure 9



A. ALGAL SUCCESSION IN POND L
(TROUT CHOW, 3% FEEDING RATE)

B. NITROGEN COMPOUNDS, ORTHOPHOSPHATES & ALKALINITY (mg/l) IN POND L
(TROUT CHOW, 3% FEEDING RATE)

C. TEMPERATURE, pH, DISSOLVED OXYGEN MIN./MAX. MID POINTS IN POND L AND SOLAR RADIATION

Figure 10

Ponds J, L and H (Figures 9A, 9B and 9C) had consecutively increasing nitrogen input rates. During the first month the consequential ammonia concentrations stayed below 1 mg nitrogen per liter in Pond J, climbed to a moderate 2-3 mg per liter in Pond L, and rose above 8 mg per liter in Pond H. In the latter pond, nitrogen input clearly exceeded fish and algae assimilation rates, even though the algae, in a steady growth phase, was undoubtedly incorporating significant amounts of ammonia. After this first peak in largely benign, ionized ammonia (NH_4^+) in Pond H, feeding in the "6%" ponds was discontinued temporarily, and then resumed at a 3% feeding rate.

The influence of the algae bloom and crash can be seen clearly in Figure 9. One to two weeks after the point in the first week of September when algae biovolumes dropped precipitously, ammonia concentrations climbed sharply. The 5 to 15 day delay was probably the time required for the sedimented cells to lyse, and for bacteria populations to increase sufficiently to decompose the dead cells. Phosphate rose simultaneously in the case of Pond L, or well beforehand, during the algae peaking, in Ponds J and H.

For all ponds, as ammonia increased, alkalinity also rose in an expected manner, since hydrogen ions are consumed as proteins decompose. (Alkalinity is carbonate plus bicarbonate plus hydroxyl minus hydrogen ions. Brewer and Goldman, 1976, detail the process.) If the ammonia is reassimilated by algae, the alkalinity should return to initial levels, whereas if the ammonia is oxidized by nitrifying bacteria into nitrite, twice as many hydrogen ions result and alkalinity should drop below initial levels. Because subsequent to the disappearance of ammonia, alkalinity returned to initial levels in Pond J, much of the ammonia nitrogen was probably reassimilated by the algal biomass. On the other hand, in Ponds L and H alklainity dropped well below initial levels, suggesting the ammonia had been nitrified (i.e., oxidized) to nitrite (NO_2) and then nitrate (NO_3). This hypothesis about different escape routes for ammonia in the ponds is supported by the sharp increase in nitrite and nitrate in Ponds L and H as ammonia disappeared, compared to the muted increase in Pond J.

A shifting network of nitrogen pathways causes the complex nitrite and nitrate fluctuations seen in the latter part of the experiment for Ponds J, L and H. Nitrite accumulates, denitrifies to nitrogen gas, or oxidizes to nitrate, depending on bacteria populations, oxygen levels, temperature and pH. Nitrate accumulates, is assimilated by algae, or reduces back to nitrite (in low oxygen situations).

Figure 9B shows the resulting fish growth. Pond D grew negligibly due to the dominance of largely inedible algae during the fertilization phase, and due to low feeding rates of comfrey, apparently an incomplete protein source, after that. The algae bloom in Ponds L and H seemed to spur growth, and the aftereffects of the algae crash seemed to harm growth. In fact, Pond L suffered extensive mortality and biomass reduction when its aeration supply was cut off inadvertently by a visitor during the critical period of intense decomposition after the algae crash. Pond N, a replicate of Pond L, continued with little mortality until the experiment ended on October 10. The ponds fed rabbit food (e.g., Pond J) did not experience the same decline in growth that the 3% and 6% trout chow ponds did. Surprisingly, growth seemed to actually accelerate, perhaps due to acceptable low ammonia and nitrite concentrations, combined with highly digestible bacteria thriving on dead algae detritus. In the end, the rabbit feed ponds grew about 4 kilograms, while growth in the "6%" trout chow ponds (the rate was actually almost 3%) averaged 5.4 kilograms.

In Figure 10 algae and water chemistry parameters are shown on one page to give the reader a complete picture of the interactions between variables previously described.

D. DISCUSSION OF RESULTS

1. Replicate Consistency

The data previously presented characterize a different complex ecosystem for each feeding treatment. Yet consistency was found between the three replicates of each treatment. For example, when Pond H indicated the first appearance and increase of nitrogen-ammonia during the third week of the experiment, replicates F and G with the same feeding treatment also exhibited substantially higher ammonia levels than all of the other treatments. Similarities in incremental growth (Figure 8B) also support replicate consistency.

2. Growth and Efficiency Under Each Treatment

a. Introduction

Efficient production of fish biomass in water solar ponds is the primary goal of the program. Measurements of growth efficiency, therefore, were examined in detail for the three significant feeding regimes in the experiment.

Negligible growth in the low-input ponds where no nitrogen source other than urine and small amounts of comfrey was introduced precluded detailed analysis for comparison with the other treatments. Ponds H (6% trout), J (3% rabbit) and L (3% trout) represent the feeding regimes where detailed water chemistry was continuously monitored. The information, together with a summary of physiochemical parameters and Secchi readings as a measure of algal activity, are presented in Tables 3, 4 and 5.

In the tables, fish growth over each period is expressed in grams of wet weight increase per day for an entire pond. For comparative purposes, fish growth and feeding rates were converted to their dry weight nitrogen content. Table 6 describes the conversion of wet weight feeds and fish to dry weight nitrogen.

Growth Period Dates	Growth g/day	N Conver Eff. %	Sunny Days % total	Weather	n	pH	dO mg/l	Temp deg C	Secchi cm	Alkal. mg/l	CO_2 mg/l	N Nutr. Excess mg/l N/day	N Water Quality mg/l **
1				Sunny	4	12.7	12.7	28.7	32.3				
7/31-	34	71	33	Cloudy	8	8.3	10.0	25.6	29.3	40	.00	.2	
8/14				total	12	9.8	10.9	26.6	30.3				
2				Sunny	7	8.2	13.2	29.2	18.5				
8/15-	11	15	58	Cloudy	5	6.0	10.1	25.2	12.6	40	1.47	1.0	
8/28				total	12	7.3	11.9	27.5	16.0				
3				Sunny	6	8.3	15.6	26.2	17.0				
8/29-	47	50	50	Cloudy	6	7.0	9.9	23.7	15.0	45	1.11	.8	
9/11				total	12	7.6	12.5	25.1	16.0				
4				Sunny	6	7.0	11.7	28.5	18.4				
9/12-	69	61	50	Cloudy	6	6.7	7.8	24.1	18.5	60	9.36	.7	N-NH_4 to 4.9
9/25				total	12	6.9	9.9	26.5	18.4				
5				Sunny	8	7.3	13.2	30.0	13.4				
9/26-	56	29	67	Cloudy	4	6.7	7.1	25.6	10.3	35	2.74	1.3	N-NO_2 to 1.1
10/10				total	12	7.1	11.2	28.5	12.4				$\bar{x}$ N-NO_2= .5
6				Sunny	18	6.8	12.5	25.9	9.9				
10/11-	45	15	62	Cloudy	11	6.6	7.7	23.4	10.2	35	6.86	1.8	N-NO_2 to 4.4
11/13				total	29	6.7	10.6	25.0	10.0				$\bar{x}$ N-NO_2= 1.9
Average	44												

** Throughout the text ammonia, nitrite and nitrate concentrations are given as milligrams nitrogen per liter. Since the literature sometimes lists them as milligrams total weight/liter, we list the conversion factors here: NH_3 = 1.22 x N-NH_3; NO_2 = 3.3 x N-NO_2; NO_3 = $4.\overline{3}$ x N-NO_3

TABLE 3. Summary of growth efficiency, nutrient excess, nitrogen water quality, and physio-chemical spot checks for pond J (Rabbit chow feed at 3% fish body weight)

Growth Period/ Dates	Growth g/day	N Conver. Eff. %	Sunny Days % total	Weather	n	pH	dO mg/l	Temp deg C	Secchi cm	Alkal. mg/l	CO_2 mg/l	N Nutr. Excess mg/l N/day	N Water Quality mg/l
1				Sunny	4	8.5	14.5	27.9	25.8				
7/31-	55	57	33	Cloudy	8	8.6	11.3	25.5	25.1	40	.10	.7	
8/14				total	12	8.6	12.4	26.3	25.3				
2				Sunny	7	8.6	16.3	28.8	12.8				
8/15-	56	38	58	Cloudy	5	8.1	11.6	25.1	8.4	40	.15	1.5	
8/28				total	12	8.4	14.3	27.3	11.0				
3				Sunny	6	9.6	17.3	26.0	8.8				
8/29-	93	50	50	Cloudy	6	7.5	11.8	23.7	9.9	42	.10	1.6	$N-NH_4$ to 1.9
9/11				total	12	8.6	13.6	25.0	9.3				
4				Sunny	6	6.5	8.5	27.6	18.1				
9/12-	*	*	50	Cloudy	6	6.5	3.9	23.9	13.6	75/20	23.36/6.23	*	*
9/25				total	12	6.5	6.4	25.9	15.9				
5				Sunny	8	6.8	10.4	28.3	15.0				
9/26-	*	*	67	Cloudy	4	6.4	4.2	25.7	12.8	25	4.91	*	*
10/10				total	12	6.7	8.3	27.4	14.3				
Average	68												

* High mortality at the beginning of growth period 4 precluded additional analysis of growth efficiencies and nutrient load for periods 4 and 5.

TABLE 4. Summary of growth efficiency, nutrient excess, nitrogen water quality, and physio-chemical spot checks for pond L (Trout chow feed at 3% fish body weight)

Growth Period/ Dates	Growth g/day	N Conver. Eff. %	Sunny Days % total	Weather	n	pH	dO mg/l	Temp deg C	Secchi cm	Alkal. mg/l	CO_2 mg/l	N Nutr. Excess mg/l N/day	N Water Quality mg/l
1 7/31- 8/14	93	49	33	Sunny	4	7.7	13.5	28.4	30.3	50	.62	1.6	N-NH_4 to 9.0
				Cloudy	8	8.0	9.6	25.5	24.8				
				total	12	7.9	10.9	26.5	28.5				
2 8/15- 8/28	40	33	58	Sunny	7	7.6	12.0	27.8	24.7	40	.31	1.3	N-NH_3 to 4.0
				Cloudy	5	8.5	10.8	24.7	20.2				
				total	12	8.1	11.5	26.5	22.8				
3 8/29- 9/11	42	12	50	Sunny	6	7.4	14.3	26.0	17.9	42	4.13	4.9	N-NO_2 to 2.0 $\bar{x}$ N-NO_2= 1.0
				Cloudy	6	6.6	7.8	23.5	15.3				
				total	12	7.0	11.1	24.9	16.6				
4 9/12- 9/25	32	17	50	Sunny	6	6.7	9.6	28.5	18.2	42	10.39	2.8	N-NO_2 to 1.7 $\bar{x}$ N-NO_2= 1.5
				Cloudy	6	6.4	6.4	23.5	12.8				
				total	12	6.6	8.1	26.2	15.5				
5 9/26- 10/10	4	1	67	Sunny	8	6.8	2.3	30.1	22.9	70	10.92	4.0	N-NH_4 to 15.0
				Cloudy	4	6.9	3.8	24.1	17.8				
				total	12	6.8	2.8	28.1	21.2				
6 10/11- 11/13	69	30	62	Sunny	18	6.0	11.3	25.7	14.4	15	18.60	1.7	N-NO_2 to 10.0 $\bar{x}$ N-NO_2= 5.4
				Cloudy	11	5.8	8.1	25.8	12.9				
				total	29	5.9	10.0	25.7	13.9				
Average	68												

TABLE 5. Summary of growth efficiency, nutrient excess, nitrogen water quality, and physio-chemical spot checks for pond H (Trout chow feed at 6% fish body weight)

Table 6. Conversion of wet weight biomass to dry weight nitrogen.

Rabbit Chow	
dry weight/wet weight	.93
protein/dry weight	.20
nitrogen/protein	.21
nitrogen/wet weight	.039
Trout Chow	
dry weight/wet weight	.93
protein/dry weight	.40
nitrogen/protein	.21
nitrogen/wet weight	.078
Fish Biomass	
protein/wet weight	.18
nitrogen/protein	.21
nitrogen/wet weight	.038

On the basis of these three assumptions, comparisons were made between food input per day (in grams nitrogen) and fish growth per day (also in grams nitrogen) for each growth period. These comparisons are summarized as percent of feed nitrogen converted to fish nitrogen, a measure of food conversion efficiency. A third total nitrogen measurement was based on feed nitrogen not assimilated by fish in incremental growth. Assuming the volume of a solar pond to be 2,300 liters, the unassimilated (by fish) nitrogen is expressed in mg/l total nitrogen per day. This measurement represents the nitrogen "load" upon the system. This organic nitrogen soon decomposes, releasing ammonia that either: 1) gets absorbed by algae, 2) oxidizes to nitrite and then nitrate by nitrifying bacteria, or 3) accumulates.

Mid-day measurements of oxygen, pH, temperature and photosynthetic depth (via Secchi disk) supplement the growth and nitrogen information. These measurements were made between 1000 and 1300 hours, when O_2, pH and temperature were rising toward peak daily values. It is also important to note that this was the time the fish were fed.

b. Fish Growth Under Good Water Quality

When treatment periods were compared in terms of fish growth efficiency, good efficiencies occurred until the appearance of stress-producing water quality: presence of un-ionized ammonia, nitrite, extremely low dissolved oxygen and extremely high carbon dioxide concentrations. These four water quality parameters are the major stresses to fish respiration, inducing mortality or inhibiting growth at sub-lethal concentrations. Each feeding treatment exhibited a different manifestation of these fish respiratory stresses over time, indicating complex interrelationships between the utilization of nutrients by algae, bacterial nitrifiers and fish.

When growth efficiencies were examined for each treatment (Tables 3, 4 and 5) during growth periods when negligible stress occurred, they proved superior to later more eutrophic conditions. Most notable is the similarity in average nitrogen conversion efficiency regardless of type of food (rabbit or trout chow) or feeding rate. That is, the tilapia appear to consistently metabolize 48-50% of the food nitrogen regardless of feed input relative to fish density. From Tables 4 and 5, the third growth period for Pond L had the same food input, growth efficiency and fish growth as the first growth period for Pond H. Yet Pond L started the third growth period with 103 fish totaling 3,560 grams wet weight, while Pond H started the first growth period with 46 fish weighing 2,000 grams. Fish in Pond H, therefore, consumed more food per individual than Pond L, yet total weight in fish per pond was the same. The range of total fish biomass in which the 49% nitrogen conversion efficiency applies appears quite wide under good water quality conditions.

From these relationships, it appears that Sarotheradon aureus can utilize only 49% of the available nitrogen in the supplemental dry feed tested. Because the fish in Ponds C, D and E, fed only algae, did not grow, and after a time seemed to lose weight, we assume the thick-walled green algae present in the ponds were not a significant source of nitrogen for the tilapia. Comparing period 3 with Pond L with period 1 of Pond H (both having a 49% conversion efficiency), the algal densities were extremely high in L while low in H. Analysis of fish feces showed that the fish did not appear to be able to efficiently lyse green algal cell walls at pH ranges found during these growth periods.

The duration of good water quality does not depend upon density of fish directly, but instead upon the excess nitrogen loading rate. A basic assumption in solar pond aquaculture is that green algae metabolize excess nitrogen and thus prevent accumulation of ammonia, nitrite and nitrate. Results presented in the summary tables support this result. At the highest feeding rate (Pond H), the nitrogen load of 1.6 mg/l per day could not be metabolized by existing populations of algae. By growth period 2, all 6% ponds (F, G, H) exhibited much higher ammonia levels than all other ponds. Algae crashes were apparent in all three 6% ponds during that period. The algae could not metabolize excess nitrogen at this food input rate. Subsequent build-up of un-ionized ammonia at the high pH of initial growth periods led to stress and subsequent reduction in growth efficiency. (See Figures 8B and 9C to see the peak in NH_3 corresponding to the slowing of Pond H growth.)

During the third growth period in Pond L, high populations of algae could successfully metabolize excess ammonified nitrogen at a nutrient load rate equivalent to Pond H's first period. Concurrent with each molecule of ammonia synthesized, the algae also absorb 6.6 molecules of carbon dioxide and produce 6.6 molecules of oxygen, further improving water quality. It is therefore not surprising that these two growth periods represented the best growth rates for the entire experiment.

Good water quality persisted longest in the 3% rabbit chow ponds (I, J, K) with the lowest nutrient load (see Table 3). For one of these ponds, J, the highest and subsequent lowest efficiencies of nitrogen conversion efficiency were found during growth periods 1 and 2, though both periods exhibited excellent water quality. Since Pond J started with a wider fish size range than most ponds, this phenomenon may simply be sampling error, caused by an underestimation of biomass between periods

1 and 2. Overall efficiency was still 49% for the first four weeks. As one might expect, nutrient load was about one half that of the 3% trout chow ponds.

c. Fish Growth Under Poorer Water Quality

Before examining the periods of lowered water quality, a review of factors affecting water chemistry and fish toxicity is needed. Table 7 summarizes the major oxygen, carbon and nitrogen transformations in the ponds. Factors affecting nitrogen dynamics are listed in Table 8. Finally, Table 9 provides an overview for comparing the concentrations at which various compounds become stressful.

Organism	Pathway Process	Simplified Biological Reaction (a,b)	Effect on pH,Alkal.	Theoretical Net Gain or Loss per mg N Unless Noted O_2 mg/l	CO_2 mg/l
Fish	Assimilation	Dissolved Org N $\rightarrow$ Org N	None	-	-
Fish	Excretion from Gills (Ammonification)	Amino Acid + 1.5 O_2 $\rightarrow$ 2 CO_2 + H_2O + NH_3(gills) $\rightarrow$ $\rightarrow$	Increase	-3.4	+5.4
Aerobic Decomposers	Decomposition (Ammonification)	$NH_4^+ + OH^- + 2\ CO_2$			
Green Algae	Assimilation	$NH_4^+ + 6.6\ CO_2 \rightarrow$ Org N + $6.6\ O_2 + H^+$	Decrease	+15.1	-20.7
Green Algae	Assimilation	$NO_3^- + 6.6\ CO_2 \rightarrow$ Org N + $OH^- + 8.6\ O_2$	Increase	+19.7	-20.7
Nitrosomonas Bacteria	Oxidation (Nitrification)	$NH_3^+ + HCO_3^- + 1.5 O_2 \rightarrow 2H^+ + NO_2^- + H_2O + CO_2 + .5\ O_2$	Decrease	-3.4	-4.3 mg HCO_3 +3.1
Nitrobacter Bacteria	Oxidation (Nitrification)	$2H^+ + NO_2^- + .5\ O_2 \rightarrow 2H^+ + NO_3^-$	Decrease	-1.1	0
All	Respiration	Glucose + 6 $O_2 \rightarrow 6\ CO_2 + 6\ H_2O$	Decrease pH	-1/mg O_2	+1.4/mg O_2

(a) Brewer and Goldman, 1976
(b) Delwiche, 1970

TABLE 7. Transformations in the nitrogen and oxygen/carbon dioxide systems.

Table 8. Factors Affecting Microbial Nitrogen Transformations.

Organism	Relationship
Aerobic Decomposers	Releases ammonia. Decomposition can occur in suspension in water column. High decomposition increases the mineralization of Ca^+ and Na^+.
Green Algae	Assimilates ammonia and nitrate. Populations grow and decline rapidly according to availability of solar energy and nutrients.
Nitrosomonas	Oxidizes ammonia to nitrite (first stage of nitrification). Generation time is 8-36 hours. Growth is limited at less than 2 mg O_2/l. No growth occurs at less than .8 mg O_2/l. Postulated: NH_3 inhibits nitrification. NH_4^+ at 60-110 mg/l does not affect nitrification. Temporary accumulation of NO_2^- can occur from slower growth rate of Nitrobacter. Optimum pH is 7.0-7.5. Acclimation to pH 5.5-6.0 takes ten days to attain previous nitrification rate.
Nitrobacter	Oxidizes nitrite to nitrate (second step of nitrification). Generation time is 8-36 hours. Growth is limited at less than 2 mg O_2/l. No growth occurs at less than .8 mg O_2/l. HNO_2 inhibits nitrification. 0.1-1.0 mg NH_3/l inhibits nitrification. At low O_2 concentrations NO_3 can reduce to NO_2 and then N_2 (denitrification). Optimum pH is 7.0-7.5. At 30°C, Nitrobacter deactivates at pH greater than 8.5 or less than 6.5

Sources:

Konikoff, 1975.
Ruttner, 1953.
Wong-Chong and Loehr, 1975.
Sharma and Ahlert, 1977.

Table 9. Factors Related to Stress and Reduced Growth in Fish.

Stress	Relationships
High Un-Ionized Ammonia NH_3	Interferes with respiration and excretion in the gills. Toxicity varies with fish species. Affects some species at less than 1.0 mg/l.
Low Oxygen O_2	Stresses respiration by reducing the passive hemoglobin transport of O_2 to tissues. O_2 (water) $\longrightarrow$ O_2 (tissue) $Hb + O_2 \longleftrightarrow HbO_2$ (reversible)
High Carbon Dioxide CO_2	Low O_2 and high CO_2 causes high CO_2 partial pressure and low O_2 partial pressure at gill interface. Resulting diminished hemoglobin-oxygen and excessive hemoglobin-CO_2 can produce anoxia in tissues.
High Nitrite NO_2^-	Oxidizes hemoglobin to methemoglobin ($Fe^{2+} \longrightarrow Fe^{3+}$). MetHb cannot release O_2 and CO_2 after binding them. MetHb increases affinity of normal Hb for O_2, further impairing O_2 supply to tissues. Active Hb reductose system in fish reduces MetHb. Bound oxyhemoglobin (Hb-O_2) is not easily oxidized to MetHb; thus high O_2 may reduce nitrite toxicity. Affects some species at less than 1.0 mg/l. Toxicity varies with fish species. At pH 5.6-5.8, H_2S + MetHb $\longrightarrow$ (anaerobic) $\longrightarrow$ MetHbS $\longrightarrow$ (auto-reductive) $\longrightarrow$ Hb. Cl^- at concentrations 15x nitrite interferes with nitrite toxicity. High Ca^{2+} interferes with nitrite toxicity. Low pH may enhance nitrite toxicity in clean water.
High Nitrate NO_3^-	Can be reduced to NO_2^- in digestion, leading to MetHb toxicity. Toxic at concentrations at least 30x that of NO_2^-. KNO_3 4x as toxic as $NaNO_3$ for bluegills.

Sources: Baird et al., 1979; Bodansky, 1951; Crawford and Allen, 1977; Harrison, 1977; Perrone and Meade, 1977

Pond H, with its high feeding rate and intense biological activity, provides an excellent context in which to discuss the toxins listed in Table 7. At different times in Pond H, each of the toxins may have had a significant impact on fish growth.

i. Pond H, Periods 1 and 2 (7/31 - 8/28):

Cloudy weather, an algae crash and a high nutrient loading rate caused ionized ammonia (NH_4^+) to build up during the first growth period (see Figure 9C and Table 5). Subsequent sunny weather pushed pH above 8.0 and shifted as much as four mg/l of ammonia-nitrogen to its toxic un-ionized form (NH_3). The reduction in growth efficiency from 49% to 33% was probably caused by un-ionized ammonia stress.

Once fish stress occurs, the resulting decrease in nitrogen assimilation accelerates ammonia formation (positive feedback). Though algae may initially outcompete nitrifying bacteria for ammonia, the intense ammonia production during periods 2 and 3 outstripped algal assimilation rates, and nitrifying bacteria had time to establish themselves.

ii. Pond H, Periods 3 and 4 (8/29 - 9/25):

Here the system becomes more complex. Nitrite levels appeared high enough to stress fish, reducing growth efficiencies to 12% and 17% in periods 3 and 4. Sharp increases and decreases of nitrate (NO_3^-) concentrations during this time were sometimes inversely correlated with algae densities (which in turn were affected by daily solar radiation). At other times it appeared that nitrate and nitrite (NO_2^-)

cycled out of phase, suggesting either: 1) an oscillation between nitrite oxidation (nitrification) and nitrate reduction (denitrification), or 2) inhibition of nitrite oxidation by high nitrate concentrations, followed by nitrate assimilation by algae, or 3) pulsing ammonia inputs causing spurts of nitrite, in turn causing influxes of nitrates. At any rate, the increased rates of change suggested that an unsteady balance now characterizes the ecosystem.

iii. Pond H, Period 5 (9/26 - 10/10):

Between September 22 and 24, an algae population crash drastically upset Pond H's water chemistry. Oxygen concentrations plummeted, indicating intense aerobic decomposition, and almost no fish growth occurred for two weeks following the crash. Ammonia accumulated in solution, either because a sufficient nitrifying bacteria population had not established itself, or because oxygen levels were low enough to inhibit nitrifying bacteria activity. Luckily, the low pH caused by rapid carbon dioxide creation forced the high levels of ammonia into its non-toxic, ionized form. Orthophosphate concentrations also climbed, since large quantities were liberated from the decomposing algae cells, and neither nitrifying bacteria or algae populations were active enough to re-absorb the phosphorous.

iv. Pond H, Period 6 (10/11 - 11/13):

During the last growth period the nitrogen assimilation efficiency rebounded to 30%, despite nitrite concentrations that climbed to 10 mg/l. This is five times the nitrite concentrations suspected of causing the low assimilation efficiencies of 17% and 12% during periods 3 and 4. The conversion efficiency for Pond H in period 6 was also twice that for Pond J, having half the nitrite concentrations. The only other measured parameter setting Pond H in period 6 apart from the other ponds cited is a lower afternoon pH (5.9 vs. 6.6-7.0).

Mechanisms that inhibit nitrite toxicity are not well delineated, although some detoxifying relationships have been reported and are listed in Table 8. Recent research suggests that sodium and calcium anions and chloride cations reduce the toxicity of nitrite (Steve Perrone, University of Rhode Island, personal communication). The low pH in Pond H during period 6 encourages speculation that low pH might also detoxify nitrite, though Perrone has found some evidence for the opposite case to be true, at least under relatively pure water conditions. As shown in the modeling section on acid base pairs, nitrite does not shift to nitrous acid until pH drops below 4. The recovery of oxygen concentrations after the extremely low levels during period 5 would also definitely mitigate nitrite toxicity to some degree.

Differences between rabbit and trout feeds make comparisons of fish growth inhibition by nitrite difficult since concentrations of detoxifying agents probably vary greatly. These detoxifying agents also probably depend on the stage of pond development, a factor clearly suggested when comparing periods 3 and 4 with period 6 in Pond H.

d. Summary of Pond Conditions that Clearly Inhibit Fish Growth

Though the relationship between nitrite and fish growth remains complex and replete with anomalies, some simple statements can be made about the growth-inhibiting effects of high un-ionized ammonia, high carbon dioxide and low oxygen concentrations:

1) When low initial algae densities are combined with a high nutrient loading rate (e.g., early periods in Ponds D and H), sudden shifts from cloudy weather (when ionized ammonia accumulates) to sunny weather (when pH rises dramatically) can result in high concentrations (over 1 mg/l) of toxic un-ionized ammonia. This appears to harm fish growth in all circumstances where it occurs.

2) In mature ponds pH drops near or below neutral, and ammonia occurs only in its relatively non-toxic, ionized form (NH_4^+).

3) Rapid decomposition from algae population die-offs produces high carbon dioxide, alkalinity and ionized ammonia levels, and depletes oxygen concentrations. The carbon dioxide and oxygen conditions half growth, and in extreme circumstances (e.g., a failed aeration system) can even kill tilapia. Afternoon oxygen concentrations below 3 mg/l indicates serious night-time oxygen depletion.

4) It is difficult to improve water quality after it has declined due to an algal crash (water quality worsens 5-15 days after a crash). Replacing large fractions of the water mass did not remedy the situation. A period of recuperation must occur before fish and algae growth revives. Foreseeing and preventing algae crashes, or siphoning immediately after a crash, may prove the most effective management strategy.

IV. EXPERIMENT #3: FISH MONOCULTURE UNDER DIFFERENT AERATION RATES

Evaluation of Solar-Algae Pond Aquatic Ecology and Fish Productivity During Winter Months in the Cape Cod Ark
(January 11, 1978, to April 4, 1979)

A. DESCRIPTION

This experiment was designed to determine the impact of varying intensities of aeration upon the aquatic ecology and fish productivity in the Cape Cod Ark. Both the water chemistry and phytoplankton population dynamics were documented through this evaluation. The experiment was initiated on January 11, 1978, through April 4, 1979, to further assess the production potential of the solar-algae ponds within the building during winter and early spring.

1. Physical Design

In this trial, Ponds 6 and 7 were used. They have the same structural components of the outdoor ponds including the double weather pane on the vertical sides. They were covered with a single layer cone on top to limit evaporation and heat loss. These two ponds are located on the upper tier in the aquaculture section of the Cape Cod Ark. The ponds had nearly equal exposure to the solar radiation penetrating the south-facing glazing; however, Pond 7 was slightly more shaded than Pond 6.

2. Aeration

The aeration scheme used a single air diffuser in Pond 6 and five of these on Pond 7. This resulted in 0.174 ft^3/min in Pond 6 and 0.773 ft^3/min in Pond 7 or a 4.4-fold difference between them. This difference in aeration insured the more highly aerated pond to have a higher minimum dissolved oxygen concentration than the other. Besides this difference, the more intensely aerated pond also had greater water turbulence. The impact of this on energy expended by the fish in additional swimming activity may cause less weight gain due to extra respiration. On the other hand, the fish could possibly find eddies within the water column. The significance of this potential difference in activity combined with differences in the evolving chemistry and ecology within the ponds would ultimately be evaluated in regard to their impact upon fish growth.

3. Fish Biomass

A monoculture of the tilapia, *Sarotheradon aureus*, was stocked in the ponds. Pond 6 was stocked with 153 fish weighing 12,152 grams and Pond 7 was stocked with 147 fish weighing 12,142 grams. The efficiency of using this relatively high biomass of fish was also to be evaluated.

4. Feeding

The fish were fed Purina Trout Chow at a very low rate. This was done to limit the necessity of frequent water exchanges. The ponds in the Ark are a major component of the building's thermal mass, and exchanging the warm water in the pond with cooler fresh water would have resulted in a net loss of heat from the building. The average feeding rate per day was 0.17% of the initial fish biomass or approximately 20 grams.

5. Procedure

The ponds were stocked on December 11, 1978. At this time each was aerated with a single air diffuser. This condition existed until January 11, 1979. At this time the water between the ponds was thoroughly mixed and an additional four air diffusers were placed in Pond 7. The fish in both ponds were fed equally from December 11, 1978, until the experiment's end. Water chemistry evaluations began on January 11, 1979, after the water was mixed.

B. WATER CHEMISTRY METHODS AND MATERIALS

This experiment included additional water testing procedures to those described in Experiment #2. Turbidity measurements were performed for 1" light path cuvettes with the Spectronic 21 meter and calibrated for formazin turbidity units (FTU). Sulfate measurements were also added to the parameters measured on a regular basis.

Chlorophyll a and pheophytin a analysis with dry weight estimates was initiated in February, 1979, to provide additional estimates of living algae and detritus proportions and inferred nitrogen biomass of each. Techniques adopted for these determinations are those outlined in *Standard Methods*. This information should allow for more accurate estimations of detrital build up in suspension and possible interferences of shading with photosynthetic activity. In addition, detrital build up may show positive effects if related to inhibition of nitrite toxicity. These methods may exhibit less variability than density approximations of algae by counting methods.

C. RESULTS AND DISCUSSION

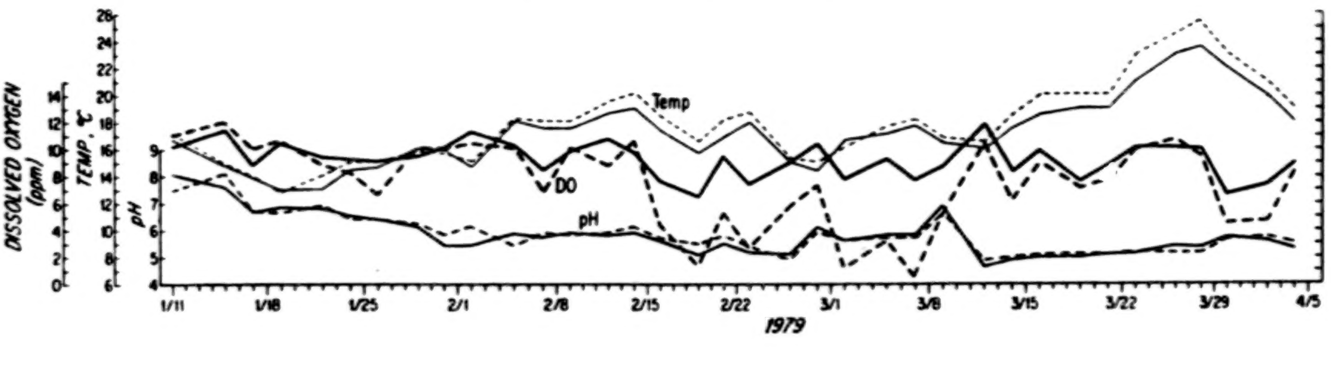
1. Fish Growth

Results of water sampling for Ponds 6 and 7 are presented with algal densities, water chemistry, and outside solar radiation in Figures 11 and 12. Most remarkable is the relative similarity between the fluctuation of the different factors measured in the two independent ponds. Physio-chemical measurements follow similar trends in the ponds with the exception of one period in Pond 6 with reduced oxygen concentrations. Algal densities are initially similar in both ponds, but higher densities soon predominate in Pond 6. Algal species differed from those found in late summer experiments.

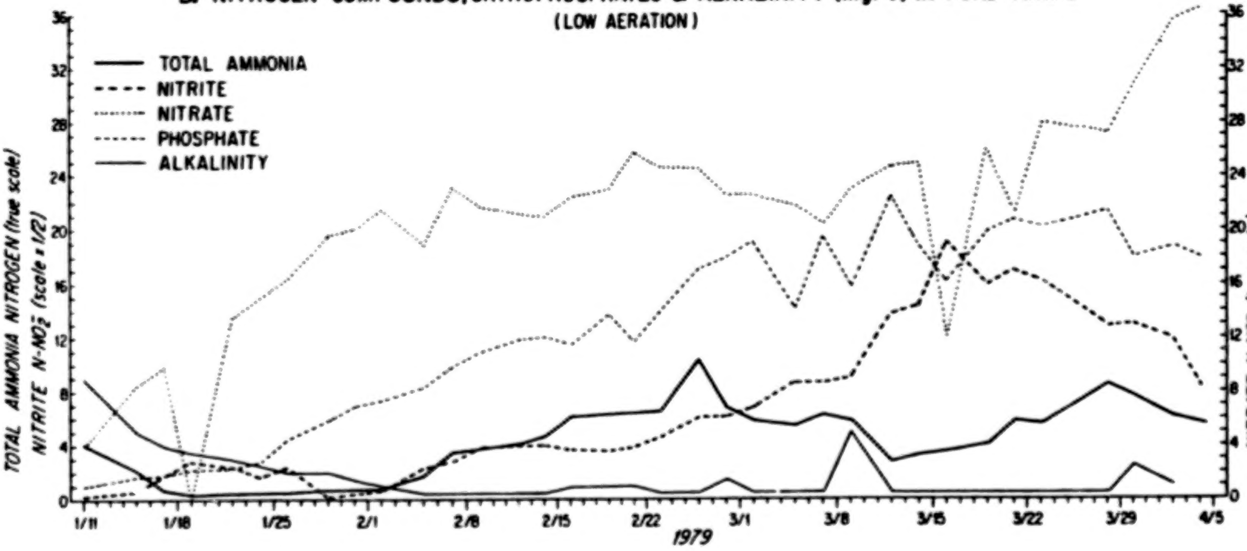
A summary of growth relationships and water quality are presented in Tables 10 and 11. Although average growth of fish per day was low (9.4 - 11.6 g/d), nitrogen growth conversion efficiency was 25% to 31.5%. When compared with water quality, the overall relationships are very similar to results for growth period 6 of Pond H for Experiment #2; that is, a higher growth efficiency than predicted in regard to the high nitrite concentrations. Average pH values during this experiment were the lowest measured for any previous

Figure 11

A. TEMPERATURE, pH & DISSOLVED OXYGEN IN POND 6 (light aeration----) & POND 7 (heavy aeration——)
AT TIME OF WATER CHEMISTRY SAMPLING



B. NITROGEN COMPOUNDS, ORTHOPHOSPHATES & ALKALINITY (mg/ℓ) IN POND ARK 6
(LOW AERATION)



C. NITROGEN COMPOUNDS, ORTHOPHOSPHATES & ALKALINITY (mg/ℓ) IN POND ARK 7
(HIGH AERATION)

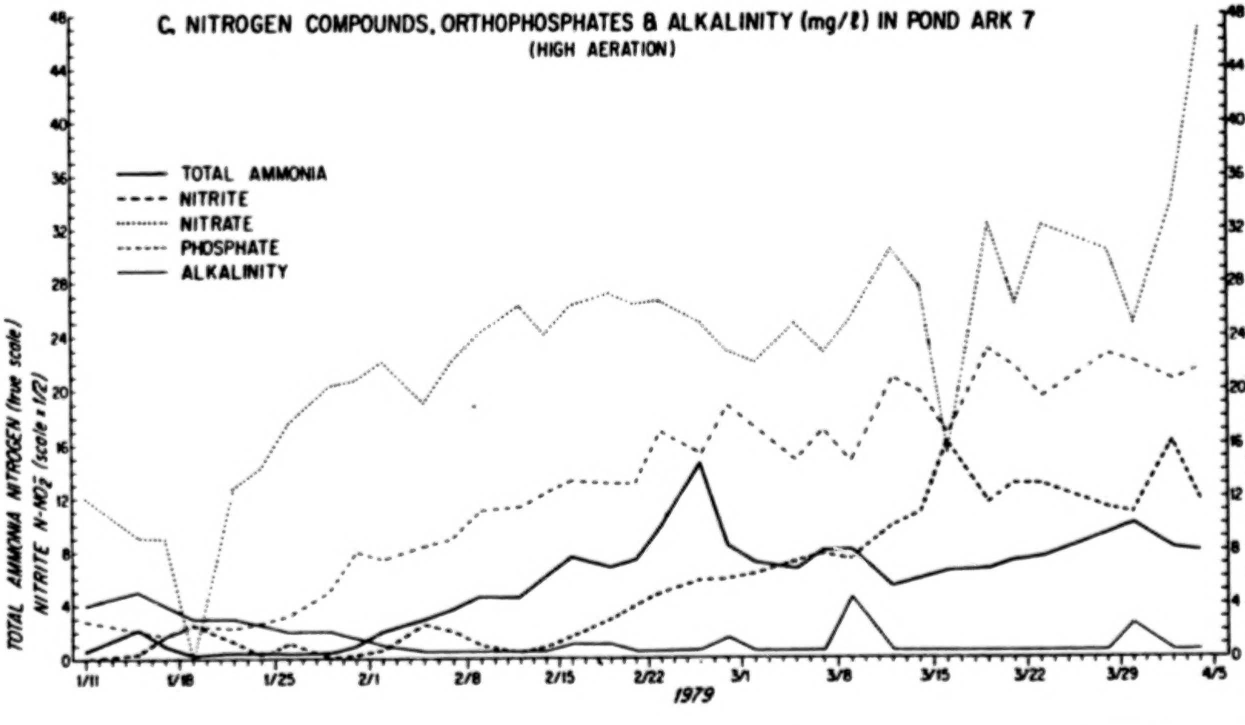
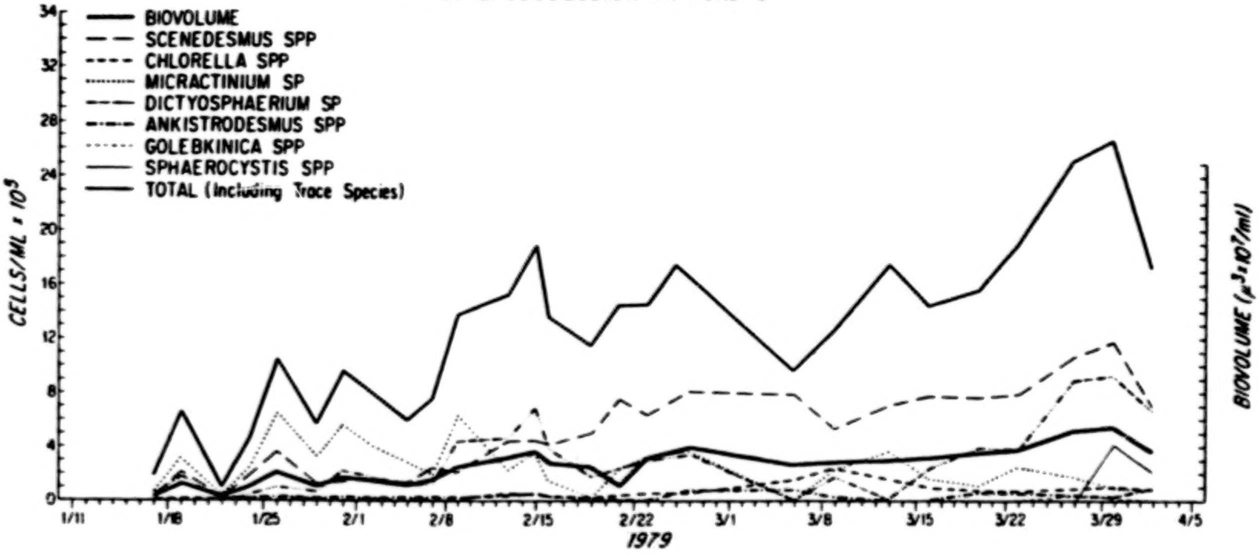
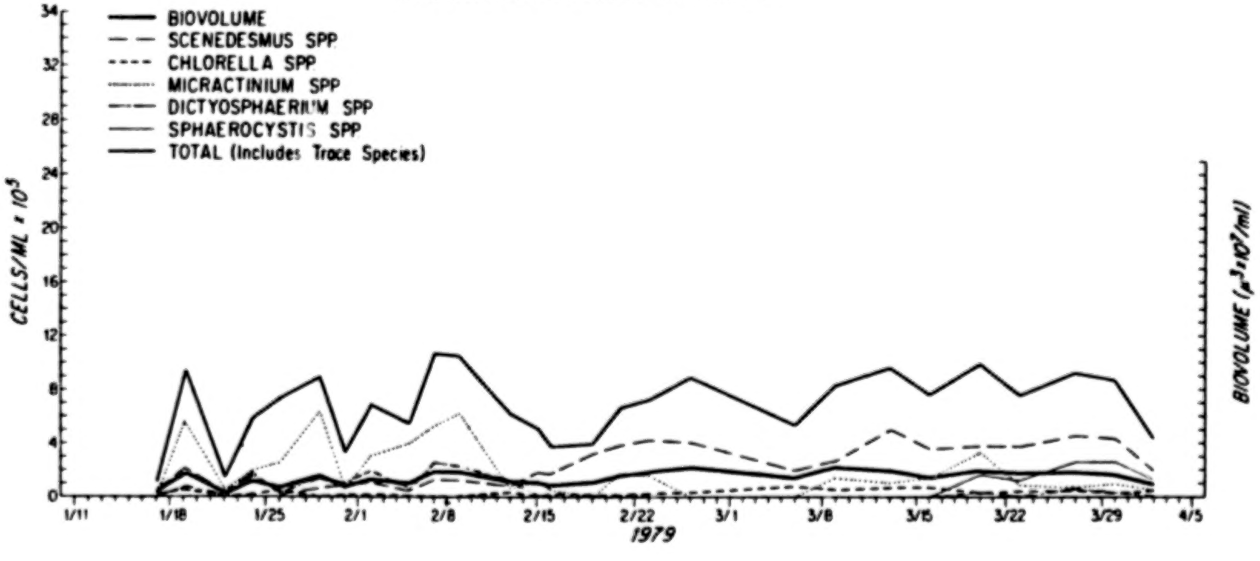


Figure 12


A. ALGAL SUCCESSION IN POND 6


B. ALGAL SUCCESSION IN POND 7

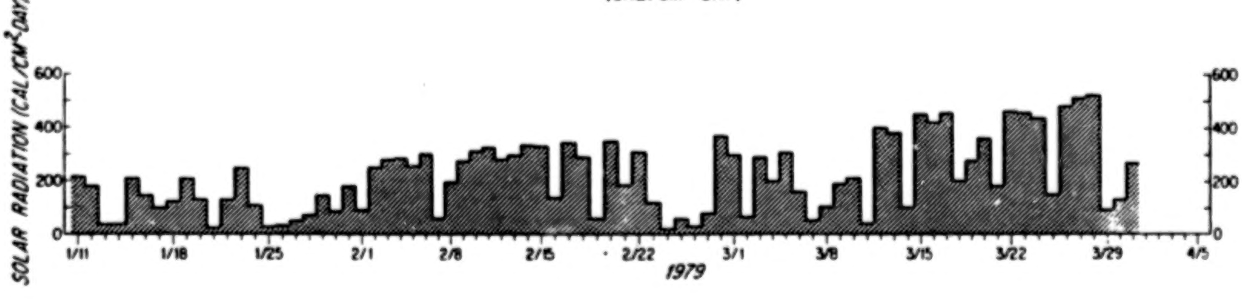

C. TOTAL DAILY HORIZONTAL SOLAR RADIATION
(CAL/CM²-DAY)

Table 10. Summary of Growth Relationships for Experiment #3.

	Pond A6 Winter 1979	Pond A7 Winter 1979
Initial fish density	12,152 g	12,142 g
Feed rate	.17% trout	.17% trout
Initial $\bar{x}$ weight/fish	79.5 g	82.6 g
Final $\bar{x}$ weight/fish	84.1 g	89.2 g
Growth period, days	83	83
Growth - net weight fish/day	9.4 g	11.6 g
N growth efficiency	25%	31.5%
N nutrient load/day	.45 mg/l	.42 mg/l

Table 11. Summary of Average Water Quality for Experiment #3.

Pond A6:

		Average Physio-Chemical				Average N-Forms and CO_2, mg/l			
Weather	# of Days	Secchi, cm.	Temp., °C	O_2 mg/l	pH	N-NH_3	N-NO_2	N-NO_3	CO_2
Sunny	17	12.2	17.7	9.1	6.0	3.6	2.7	18.9	--
Cloudy	18	10.7	17.7	5.6	5.7	4.9	4.0	22.9	--
Total	35	11.3	17.7	7.4	5.8	4.2	3.3	20.9	6.9

Pond A7:

		Average Physio-Chemical				Average N-Forms and CO_2, mg/l			
Weather	# of Days	Secchi, cm.	Temp., °C	O_2 mg/l	pH	N-NH_3	N-NO_2	N-NO_3	CO_2
Sunny	17	13.1	17.2	10.0	6.1	4.3	2.0	20.8	--
Cloudy	18	12.6	16.9	8.4	5.6	6.5	3.5	25.0	--
Total	35	12.8	17.1	9.2	5.8	5.4	2.8	22.9	6.6

experiment, suggesting very active nitrification. To check for the build up of bottom sediments, a single 10% draindown of each pond on February 27, 1979, revealed the bottom free of any significant detritus. Examination of water from the bottom of the pond found no H_2S present, nor any other indicators of anaerobic activity. As a result, the presence of nitrite toxicity inhibitors were suspected.

A difference between the aeration rates for the two ponds was shown in oxygen concentration variations: at water sampling times average dissolved oxygen was higher in Pond 7 (9.2 mg/l) than in Pond 6 (7.4 mg/l). Pond 6 experienced some low day-time oxygen levels between February 19 and March 9, a period of reduced insolation. This decrease marked the point in time when algal species shifted to a predominance of Scenedesmus spp. for both ponds (see Figures 11 and 12). Throughout, algal densities appeared lower in Pond 7, although the extra aeration in Pond 7 seemed useful for ponds of depressed oxygen or high BOD conditions.

The lower oxygen concentrations found in Pond 6 may have induced stress to fish, thus accounting for the slightly lower growth efficiency of 25% as compared to 31.5% of Pond 7. This also suggests that the increased water turbulence in Pond 7 did not significantly increase the amount of energy expended by the fish through extra swimming effort.

In a comparative study from the previous winter (1977-1978), better growth rates were reported for Pond 3 on the lower tier in the Ark. This trial is summarized and compared with other selected growth trials in Table 12. This pond exhibited excellent growth and growth efficiency (69%).

Table 12. Comparison of Growth Relationships for Late Summer, 1978, and Winter, 1977-1978, Experiments.

	Pond L (N) Late Summer 1978	Pond J (K) Late Summer 1978	Ark Solar Pond Winter 1977-1978
Initial fish density	2,000 g	2,000 g	860 g
Feed rate	3% trout	3% rabbit	4.5% trout
Initial $\bar{x}$ weight/fish	19.6 g (50 g)	18.5 g (40 g)	2.6 g
Final $\bar{x}$ weight/fish	47.2 g (115 g)	39.2 g (85 g)	22.3 g
Growth period, days	42	56	138
Growth - wet weight fish/day	68 g	41 g	48 g
N growth efficiency	48%	49%	69%
N nutrient load/day	1.30 mg/l	.70 mg/l	.35 mg/l

The fish in the pond were also fed Purina Trout Chow. The main difference between this pond and Ponds 6 and 7 is that it has much greater exposure to solar radiation. Also, winter 1977-1978 was much brighter than that of 1978-1979, compounding this factor. Thus, algal assimilation efficiency would be expected to have been better in the 1977-1978 period.

If the ponds of Experiment #2 are compared with the high growth of the 1977-1978 winter period, the latter's growth rate surpassed that in Pond J. Differences in fish size and biomass offer a possible explanation. Low density and very small fish (average - 2.6 grams) were used at the outset of the 1978 winter experiment. These small fish may be more efficient in assimilating the supplemental feeds. Alternatively, feeds indigenous to the pond (e.g., algae) may have provided a larger portion of their diet.

2. Nitrogen Assimilation and Algae Biomass

Chlorophyll a measurements were made on samples taken from Ark Ponds 6 and 7 between February 15 and April 2, 1979. Estimates based upon chlorophyll a determinations are presented in Table 13. Before averages of biovolume and chlorophyll a were considered, respective values for each sample day were plotted. This plot suggested that a rough linear relationship existed between biovolume and chlorophyll a within limits of the respective estimated variability. The approximate relationship is: biovolume ($\mu 3$) = 8 x chlorophyll a (mg/m^3). More controlled comparisons between these parameters are planned in future experiments.

Table 13. Summary of Chlorophyll *a* Estimates of Algal Density, Associated Biovolume Estimates, and Detrital Contribution to Total Organic Turbidity of Experimental Tanks, Winter 1978.

	Pond A6	Pond A7
Sample period	2/15 - 4/2	2/15 - 4/2
Sample number	9	9
$\bar{x}$ biovolume	6.9 E7 μ^3/m^3	3.1 E7 μ^3/m^3
$\bar{x}$ total dry weight - suspended material	1.550 E5 mg/m^3	1.101 E5 mg/m^3
$\bar{x}$ total chlorophyll *a* (adj. for pheophytin *a*)	.913 E3 mg/m^3	.464 E3 mg/m^3
$\bar{x}$ estimated dry weight living algae	.612 E5 mg/m^3	.311 E5 mg/m^3
$\bar{x}$ estimated detritus, non-algal suspended organisms	.938 E5 mg/m^3	.790 E5 mg/m^3
Living algae/total detritus	40.5%	28.4%

For both chlorophyll a and biovolume average estimates of algal densities, Pond 6 supported about twice the algal density of Pond 7. Lower average N-NO_3 concentrations in Pond 6 (20.9 mg/l) than Pond 7 (22.9 mg/l) indicated a higher algal assimilation for the higher density pond. The probable reason for density differences was that Pond 6 was exposed to a greater amount of solar radiation. Dry weight estimates of algae from chlorophyll a and total dry weight plankton measurements were used to deduce the zooplankton and detritus components of the ponds (Table 14). These estimates are similar for Pond 6 (0.938E5 mg/$m^3$0) and Pond 7 (0.790E5 mg/m^3). Nitrogen content of the food is low (6.8%), and a majority of the mass most likely contributes to the suspended solid wastes. This data might also suggest that other consumer organisms, if present, exist in relatively equal densities in the two ponds.

Certain relationships between algal assimilation efficiency and nitrification were unexpected in the winter data on the basis of predictions from the earlier experiments. Pond L in Experiment #2 exhibited an average algal assimilation efficiency of 1.3 mg/l nitrogen nutrient load per day. From biovolume estimates for Pond L and winter Pond 6, Pond 6 algae (at one-third the density of Pond L) should have been able to assimilate 0.33 x 1.3 = 0.43 mg/l nutrient load. The sudden initial appearance and steady increase of nitrification by-products was not predicted by these assumptions, and this offers insight into the effect of seasonal insolation and temperature differences on algal assimilation.

Table 14. Nitrogen Distribution at End of Experiment #3.

	Pond A6	Pond A7
*1 Residual $N\text{-}NH_3$	1.5 mg/l	7.4 mg/l
*1 Residual $N\text{-}NO_2$	4.1 mg/l	5.9 mg/l
*1 Residual $N\text{-}NO_3$	32.3 mg/l	34.7 mg/l
Total residual N-Forms	37.9 mg/l	48.0 mg/l
Total N nutrient load (mg/l/d x grow period)	37.4 mg/l	34.9 mg/l
Excess N nutrient load available for all organisms except fish	- .5 mg/l	13.1 mg/l
*2 Rough estimate N bound by algae	2.1 mg/l	.6 mg/l
Nitrogen in organisms other than fish and green algae	- 2.6 mg/l	12.5 mg/l

*1-Residual N form equal to difference between concentrations at end and at beginning of experimental growth period.

*2-Assumption 2% N in biomass determined by chlorophyll a for algae at end of growth period.

From chlorophyll a estimates for Pond 6, average algal biomass was calculated to be 0.612E5 mg/m^3 x E5 = 61.2 mg/l. If 2.0% of the algae is nitrogen, Pond 7 algae kept an average of 1.22 mg N/l in biomass. Pond L would have 2.4 - 3.66 mg N/l in algal biomass. From calculated nutrient loads, it is evident that assimilation of nitrogen loads is more efficient with rapid algal turnover, combined with consistent removal of dead algal cells.

With the ponds in the winter 1978-1979 experiment, there was only the one 10% draindown. In addition, substantially lower temperatures were probably a strong factor in reduced assimilation efficiency. An algal density might be one-third or one-half that of a summer density, but turnover rates at lower temperatures might decrease assimilation efficiencies by more than one-half or one-third. In addition, once nitrification organisms become established, they have by-products inhibitory to algal growth.

Another aspect of winter pond conditions was demonstrated in a study of residual nitrogen compounds in the pond water at the end of the experiment (Table 14). For Pond 6, all nitrogen from the food is accounted for in various estimates within that found dissolved in the water column, or in algal biovolume/chlorophyll a assumptions. However, any nitrogen appearing through decomposition has a relative 20% nitrogen return (Ruttner, 1953), that is, 20% of the nitrogen load may be bound in detritus for periods longer than the length of this trial. Thus, these estimates for Pond 6 might be interpreted to suggest nitrogen input from sources other than that supplied by the feed. Blue-green algae, nitrogen-fixers, were found on the sides of the winter ponds and further support this possibility.

If nitrogen fixation by blue-green algae occurred to an appreciable degree in Ponds 6 and 7, it may have been in a digestible species and this would account for higher growth efficiencies. There is also the possibility that ions capable of inhibiting nitrite toxicity became concentrated in the pond neutralizing the impact of this growth-inhibiting nitrogen compound. This is a potential trade-off in regard to implementing draindown strategies. Although draining removes detritus and thus reduces BOD, it also dilutes those cations which have proven effective in neutralizing nitrite toxicity.

Another management technique was tested on March 9 and March 30, 1979, in Ponds 6 and 7. The ponds had become quite acidic through the course of the experiment, with pH measurements fluctuating between pH 4.5 to 5.5. Thirty-five grams of slaked lime (CaO) was added as an alkaline buffer to each pond ($CaO + CO_2 \longrightarrow CaCO_3$). Both ponds experienced an increase in pH during the four-hour innoculation. Although both ponds started at equal pH conditions, Pond 6 was brought up to pH 6.5 and Pond 7 rose to pH 7.5. Alkalinity likewise increased, with Pond 7 going somewhat higher than Pond 6 (see Figures 11 and 12). This higher alkalinity and pH stimulated faster nitrification, with a subsequent return to the pre-existing pH within three days. It appears that a strong negative feedback system is in effect, where low pH inhibits nitrification, and nitrification drives pH downward. Buffering pH upwards would require constant titration. Benefits of this strategy have not been determined.

3. Summary of Relationships

1) Winter growth periods were characterized by algal densities lower than, and a species composition differing from, summer ponds.

2) Algal efficiencies of nitrogen load assimilation may be lower than predicted by their densities. Assimilation efficiency may be determined by temperature, quantity of available solar radiation or other factors.

3) Juvenile tilapia, *Sarotheradon aureus*, may incorporate more of the nitrogen in fish feeds or algae than older, larger tilapia.

4) Increased aeration to ponds during periods of high decomposition may be an effective management tactic until relative stability of good water quality returns.

5) Both winter ponds experienced higher growth efficiencies than expected on the basis of nitrite concentrations in Experiment #2. Inhibition of nitrite toxicity by residual anions and cations is suspected.

6) A management technique of pond water dilution may prove useful in extending efficient growth periods.

V. EXPERIMENT #4: COMPARATIVE GROWTH EVALUATION: MONOSEX HYBRID TILAPIA VS. Sarotheradon aureus MIXED SEX POPULATION

A. DESCRIPTION

1. Overview

Four solar-algae ponds on the upper tier in the aquaculture section of the Cape Cod Ark were used to compare the growth of all-male hybrid crosses (*Sarotheradon mossambicus* female x *S. honorum* male)* with the tilapia, *Sarotheradon aureus*.** Monosex x hybrids have been reported to be more efficient converters of feed into flesh, in part through bypassing precocious sexual activities. Also, the males of the species have been known to grow more quickly due to less energy required in gamete production. This phenomena was evaluated under the aquatic ecologies of the solar-algae ponds.

2. Physical Design

The ponds were double-walled without covers. They were each aerated by a single air diffuser.

3. Fish Biomass and Feeding Rate

Equal masses of live fish were stocked in four adjacent ponds within the Ark. The total weight of each group was 111 grams. Ponds 6 and 7 contained 109 and 150 *S. aureus* individuals respectively. The hybrids were stocked at 165 individuals in both Ponds 8 and 9. The fish were fed at 5% wet body with dry feed - Purina Trout Chow. This calculation was made weekly and a 1.0 s conversion was assumed.

---

* These fish were donated to us from Natural Systems, Inc., in Palmetto, FL.

**These fish were hatched from the New Alchemy stock.

B. RESULTS

The fish in each pond were fed a total of 1,667 grams of feed during the 76 day trial ending on November 1, 1978. The growth results are in Table 15.

Table 15. Blue tilapia (Ponds 6 and 7) versus tilapia hybrid (Ponds 8 and 9) growth in Experiment #4.

s Conversion	Pond	# Fish Sampled	Total Weight	Average Weight per Fish	Calculated Total Population Weight	Total Growth
1.4	6	40/109	490.6	12.27	1,336.9	1,225.9
1.5	7	49/149	403.0	8.22	1,224.8	1,113.8
0.8	8	48/164	651.0	13.56	2,223.8	2,112.8
0.6	9	45/165	648.5	14.41	2,377.7	2,266.7

C. DISCUSSION

From these results it is evident that the hybrid fish had nearly twice the growth rate and efficiency of the *S. aureus*. Although the fish were small and probably hadn't reached sexual maturity, the male hybrids had a tremendous growth advantage over the mixed-sex single species population. This hybridization proved to be superior to the New Alchemy stock of blue tilapia.

D. SUMMARY OF EXPERIMENT #4

The significance of these results indicate that for maximal fish productivity in the solar-algae ponds either a hybrid or a selected all-male population of tilapia would be the most efficient organisms to use for this genus. Methods using male hormone treatments upon fry in the first weeks of development have also proven to be useful in creating an all-male population from normal parents. Strategies using these techniques will be evaluated in future experiments.

VI. ENHANCING THE COMPUTER SYSTEM FOR DATA ACQUISITION AND ANALYSIS

At the end of one year of operation we assessed our computer system in light of our present and anticipated needs. As originally configured, the system consisted of two linked computers. One computer would specialize in analyzing information. A data acquisition microcomputer manufactured by Microlog of Guilford, Connecticut, and a PDP-11/03 computer manufactured by Digital Equipment Corporation of Maynard, Massachusetts, were selected. Together they produced a cost effective solution.

The PDP-11, as our central computer, has an excellent library of resource programs. One of the most powerful tools available in our computer library is DYNAMO, a computer language for representing non-linear feedback systems. We first attempted to install NDTRAN, a language similar to DYNAMO, but found the NDTRAN language compiler too large to fit on our flexible magnetic storage disks. We then turned to Pugh-Roberts, Inc., of Cambridge, Massachusetts, the developer and vendor of DYNAMO. Expanding the PDP-11's original 20K of core memory to its 28K maximum made it possible to operate the DYNAMO compiler. Under the direction of Dr. Schaffer at Pugh-Roberts we split the DYNAMO language compiler into two phases and managed to barely squeeze each section onto its own floppy disk. This is the first installation of DYNAMO onto a computer that uses flexible disk storage.

During the first version of the Microlog, the PDP-11 had to continuously control the Microlog's data acquisition functions. As operated the first year, the Microlog computer depended on the PDP-11 for timing, control and storage. Limited to a small storage and memory capability, including only a simple machine language program, the Microlog could only read analog signals and transmit the information to the PDP-11 for storage.

Increased frequency of analytical work forced a reassessment of the original computer linkage configuration. Initially, we believed the PDP-11 could operate in a task sharing mode. The foreground task was to be a program to communicate and store data on the PDP-11's floppy disks. The background task of editing and compiling other programs would be performed simultaneously with the foreground task. However, while executing DYNAMO or some other large programs the PDP-11 is not capable of controlling the satellite computer. Therefore, concomitant to increasing the size of the PDP-11, the capabilities of the Microlog were also expanded to allow for the increased analytical usage of the PDP-11.

Recent improvements in the Microlog have eliminated the need for a constant link to the PDP-11. The components added to the microcomputer included: 1) a micro-cassette data storage system, 2) a real time and date clock, and 3) increased memory capacity. In addition, the simple machine language instructions were replaced by a special subset of the Dartmouth BASIC computer language. Developed jointly by New Alchemy and Microlog, the BASIC interpreter has special commands to facilitate both data collection and communication with the PDP-11.

Monitoring and control configurations for the experiments originally controlled by FORTRAN programs in the PDP-11 are now controlled by the

Microlog programs written in BASIC. Although still linked to the PDP-11, the Microlog computer can function as an independent data acquisition system. The BASIC programs collect data at intervals determined by the Microlog's own clock, store data on micro-cassettes, and spool it back to the PDP-11 for further storage and analysis.

During the past one and a half years of operation, we have found the Microlog/PDP-11 linked system to be both reliable and useful. The computer system has been developed to the point where it can now meet all anticipated data acquisition and analysis needs.

VII. MATHEMATICAL MODELS

A. INTRODUCTION

In one way, this entire report is part of the modeling, or theory-forming, process. The previous sections provide two major steps in the modeling of complex systems:

1) The reference run - in this case the detailed chemical and biological histories of the ponds in the experiments. This time series data, if reproduced by the model, lends validity to the model. If the model fits this recorded data, it bolsters our confidence in runs of the model where factors differ from the situations previously monitored.

2) The verbal description of the system, particularly the causal relationships between its subcomponents. From this description, the causal loop and DYNAMO flow diagrams are drawn, and finally the verbal description is translated into quantitative relationships and computer code. An accurate mathematical model rests on an accurate verbal description.

In this section we concentrate on the last step: synthesizing and manipulating quantitative data, and translating verbal descriptions to mathematical equations. We begin with statistics programs that determine such things as the uncertainty surrounding a data point, or the probability that a difference in the data isn't just random chance. The next series of programs quantify single causal relationships from information in the literature; specifically, stochiometric information is used to determine the relative proportion of toxic to non-toxic ammonia, and nitrous acid to nitrite, indicated by a given pH. Then data conversion programs are described that derive new information from the collected data; specifically, to evaluate carbon dioxide levels from pH and carbonate alkalinity, and the total biovolume of algae from speciated algae cell counts. Additionally, SOLAR2 (a modified version of SOLAR1, described in the May 23, 1978, progress report) derives the amount of solar energy entering the ponds from data on horizontal radiation. All programs described to this point are written in the computer language FORTRAN.

This section ends with two models that have direct implications for fish culture techniques in solar-algae ponds. The first is a simple model of fish growth and food conversion efficiencies, also written in FORTRAN. It assumes unchanging water quality. Though the critical negative feedback loop from feeding rate to water quality to fish growth is not included in the model, very interesting results are suggested that need to be compared with the results of more complex models that include water quality.

The second model is a diurnal representation of the solar and chemical dynamics of the solar-algae ponds. Unlike the preceding programs, this model is written in the computer language DYNAMO. The important conclusions to be drawn from the model involve optimum aeration scheduling in ponds with high algal photosynthesis.

B. STATISTICS PROGRAMS

One of the most frequently used programs written for the PDP-11 is a simple statistics program that computes the standard deviation of a data string, the data's mean, and the standard deviation of the mean (also called the standard error). For instance, after weighing a sub-population of fish in the solar-algae ponds, it is necessary to know the standard deviation of the individual fish weights,

$$s = \frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}$$

where x_i = individual fish weights, n = sample size and $\bar{x}$ = mean; their mean weight,

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \qquad ;$$

and the standard deviation of the mean fish weight, s of $\bar{x} = s/\sqrt{n}$ To obtain a range around the mean having a given uncertainty, the standard error is multiplied by the appropriate student's t factor, determined by sample size and desired uncertainty.

A more complex program analyzes the oxygen, pH and Secchi disk readings taken for each of the 12 ponds almost every day during Experiments #1 and #2. The purpose of the program is to determine whether each group of these replicates differs consistently and significantly from the other groups. For each day, the program calculates the average dissolved oxygen concentration (or pH, or Secchi) and then the amount each pond differs from this average. For all days sampled, the differences are totaled and averaged for each pond, and the standard deviation of that average is calculated. The three replicates for each treatment regime are then averaged, and its standard deviation is also calculated. A listing and run of one of the resulting SPOT programs, DOSPOT, is shown in Tables 16, 17 and 18. Morning oxygen readings from the first experiment provide the data base.

Table 16. A Run from DOSPOT.

```
.RUN DOSPOT

  MEAN      S.D.
   1.06     0.284
  -0.09     0.364
   0.18     0.265
  -1.25     0.294
  -0.81     0.263
   0.98     0.318
   0.31     0.210
  -0.48     0.404
   0.36     0.242
   0.38     0.257
  -1.49     0.366
   0.84     0.356
        CA.NH  CA.HB  NA.NH  NA.HB
MEAN    -0.24   0.26   0.51  -0.54
S.D.     0.17   0.17   0.16   0.19
STOP --
```

Table 17. Program Listing of DOSPOT.

```
.R PIP
*TT:=DOSPOT.FOR
        DIMENSION A(12,33),B(12,33),T(33),X(33)
        DIMENSION TC(12),XC(12),SS(12),SD(12)
        DATA A/
       * 09.0,03.0,03.8,03.6,02.8,04.5,09.5,05.8,05.5,06.2,04.8,05.0,
       * 09.0,11.0,07.8,10.5,07.0,08.6,11.6,15.2,12.9,08.8,11.8,10.8,
       * 10.0,05.0,05.2,05.2,05.4,08.2,07.3,11.8,10.1,07.7,07.7,11.6,
       * 11.2,05.8,08.4,11.6,10.4,09.5,10.0,13.4,11.0,09.8,12.4,13.8,
       * 10.9,04.0,07.5,08.5,11.5,05.6,07.5,12.2,06.2,08.6,07.3,09.0,
       * 10.2,03.4,03.2,04.4,04.0,04.6,04.4,06.5,04.4,04.8,04.4,05.8,
       * 06.2,03.2,04.4,07.0,05.4,04.1,07.5,08.0,07.3,03.3,07.7,07.7,
       * 10.2,11.6,10.4,11.4,12.0,11.3,08.1,06.4,10.1,09.5,06.0,10.0,
       * 02.0,01.6,01.4,01.5,01.0,01.0,01.2,01.2,00.8,00.8,01.5,01.8,
       * 05.6,03.2,03.7,03.6,02.2,03.2,02.6,03.6,02.6,01.8,01.2,02.3,
       * 08.5,07.8,09.1,09.4,08.6,09.5,10.0,10.0,09.6,09.5,08.6,08.8,
       * 09.2,05.6,09.1,08.3,06.6,09.9,10.7,07.3,09.7,08.8,10.5,07.5,
       * 10.2,10.2,10.4,10.2,08.5,10.4,11.0,10.8,11.0,11.0,11.5,11.2,
       * 10.2,10.4,10.8,10.7,09.8,10.8,11.2,11.1,11.4,11.3,11.4,11.2,
       * 09.3,09.0,08.5,07.2,06.2,09.7,09.2,09.5,09.2,08.8,05.9,09.9,
       * 09.6,08.8,07.4,03.8,03.8,07.8,08.6,07.8,09.6,09.8,08.4,08.0,
       * 04.8,03.2,03.4,01.6,02.1,03.2,03.8,03.2,03.4,04.4,01.6,02.4,
       * 12.0,10.6,09.4,04.3,06.2,10.0,06.6,04.6,05.8,10.8,04.0,05.8,
       * 09.8,08.5,06.0,04.1,03.3,08.6,07.6,05.0,08.2,08.2,03.0,04.2,
       * 04.3,04.1,04.6,04.4,02.6,06.7,03.8,02.0,03.3,07.8,00.4,03.7,
       * 02.5,01.2,02.9,00.7,01.4,03.1,02.0,00.5,01.7,02.4,00.3,01.6,
       * 06.4,05.8,08.4,06.2,03.8,09.8,03.7,04.3,07.5,07.0,00.5,06.4,
       * 01.9,02.1,05.0,00.3,01.5,06.1,05.3,00.5,01.5,03.5,00.1,03.4,
       * 04.1,05.6,05.8,01.7,04.6,04.6,04.7,01.7,05.2,06.4,00.4,06.0,
       * 01.4,02.2,01.6,00.2,01.2,02.9,01.2,01.1,02.4,03.0,00.5,03.8,
       * 03.4,03.0,03.0,00.5,03.0,04.5,03.0,01.1,02.7,02.6,00.6,06.4,
       * 00.8,00.4,00.2,00.2,00.4,00.6,00.4,00.1,00.2,00.3,00.3,00.5,
       * 09.8,11.8,06.3,03.4,06.8,12.0,06.4,00.8,06.8,08.8,00.5,03.7,
       * 08.3,09.2,08.9,02.5,08.8,12.0,08.4,03.8,11.8,07.8,03.4,13.8,
       * 03.2,02.8,08.2,00.3,03.1,06.4,03.0,01.4,02.0,01.7,00.9,11.0,
       * 02.6,03.3,03.2,00.2,03.5,03.8,04.8,02.1,06.6,05.4,01.0,04.9,
       * 02.2,04.5,02.8,00.1,02.8,05.1,02.2,00.2,00.1,00.3,00.5,03.0,
       * 03.1,04.1,02.3,00.1,02.1,03.3,02.0,00.1,00.3,00.8,00.3,01.8/
```

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Table 18. Program Listing of DOSPOT, continued.

```
        DO 150 K=1,33
        T(K)=0
        DO 100 J=1,12
        T(K)=T(K)+A(J,K)
100     CONTINUE
150     X(K)=T(K)/12.
        DATA B/396*0./
        DO 250 K=1,33
        DO 200 J=1,12
        B(J,K)=A(J,K)-X(K)
200     CONTINUE
250     CONTINUE
        DO 450 J=1,12
        TC(J)=0
        XC(J)=0
        DO 400 K=1,33
400     TC(J)=TC(J)+B(J,K)
450     XC(J)=TC(J)/33.
        DO 550 J=1,12
        SS(J)=0
        SD(J)=0
        DO 500 K=1,33
500     SS(J)=SS(J)+((XC(J)-B(J,K))**2.)
        SD(J)=(SS(J)/32.)**.5
550     SD(J)=SD(J)/(33.**.5)
        TYPE 575
575     FORMAT (3X,'MEAN',5X,'S.D.')
        DO 650 J=1,12
        TYPE 600,XC(J),SD(J)
600     FORMAT (2X,F6.2,3X,F6.3)
650     CONTINUE
        XC10=(XC(2)+XC(3)+XC(5))/3.
        XC11=(XC(1)+XC(4)+XC(6))/3.
        XC00=(XC(7)+XC(10)+XC(12))/3.
        XC01=(XC(8)+XC(9)+XC(11))/3.
        SD10=(SD(2)+SD(3)+SD(5))/(3.*(3.**.5))
        SD11=(SD(1)+SD(4)+SD(6))/(3.*(3.**.5))
        SD00=(SD(7)+SD(10)+SD(12))/(3.*(3.**.5))
        SD01=(SD(8)+SD(9)+SD(11))/(3.*(3.**.5))
        TYPE 700
700     FORMAT (7X,'CA.NH',2X,'CA.HB',2X,'NA.NH',2X,'NA.HB')
        TYPE 750,XC10,XC11,XC00,XC01
750     FORMAT (X,'MEAN',3X,4(F5.2,2X))
        TYPE 800,SD10,SD11,SD00,SD01
800     FORMAT (X,'S.D.',3X,4(F5.2,2X))
        END
```

C. RELATIVE PROPORTIONS IN ACID/BASE PAIRS

The ratio of any acid/base pair (in this case NH_4^+/NH_3 and HNO_2/NO_2^-) dissolved in an "infinitely dilute" aqueous solution can be deduced from two factors: 1) the hydrogen ion concentration, i.e., 10^{-pH}, and 2) the appropriate dissociation constants (Trussel, 1972). The relevant dissociation constants in our case are:

K_w ionization product of water = $(OH^-)(H^+) \doteq 10^{-14}$, pK = 14.*

K_{NH_3} basicity constant of ammonia = $(NH_4^+)(OH^-)/(NH_3) \doteq 10^{-4.8}$, pK $\doteq$ 4.8.

K_{HNO_2} acidity constant of nitrous acid = $(NO_2^-)(H^+)/(HNO_2) \doteq 10^{-3.4}$, pK $\doteq$ 3.4.

(Stumm and Morgan, 1970, pp. 77-78. Weast, 1977-1978, pp. D-153 and 154.)
*Temperature slightly affects all three dissociation constants.

Algebraic juggling of the previous definitions of dissociation constants gives us the acid/base ratios:

$$(NH_3)/(NH_4^+) = K_w/(H^+)K_{NH_3} = 10^{(pH + pK_{NH_3} - pK_w)}$$

$$(HNO_2)/(NO_2^-) = (H^+)/K_{HNO_2} = 10^{(pK_{HNO_2} - pH)}$$

The ratio of the numerator to the sum of the acid and base (numerator plus denominator) is simply: R/(1+R), where R equals the base/acid or acid/base ratio derived above.

The program's runs and listings are shown in Tables 19-22. A chart similar to Table 19 was made by Trussel (1972), but does not encompass the pH range occurring in the solar-algae ponds.

Table 19. NH3PH, A Chart of the Fraction of Ammonia in Its Un-Ionized Toxic Form, As a Function of pH and Temperature.

```
.RUN NH3PH

TEMP,C: 0        5        10       15       20       25       30       35       40
PH
 5.0  0.00001 0.00001 0.00002 0.00003 0.00004 0.00006 0.00008 0.00011 0.00016
 5.2  0.00001 0.00002 0.00003 0.00004 0.00006 0.00009 0.00013 0.00018 0.00025
 5.4  0.00002 0.00003 0.00005 0.00007 0.00010 0.00014 0.00020 0.00028 0.00039
 5.6  0.00003 0.00005 0.00007 0.00011 0.00016 0.00023 0.00032 0.00045 0.00062
 5.8  0.00005 0.00008 0.00012 0.00017 0.00025 0.00036 0.00051 0.00071 0.00099
 6.0  0.00008 0.00012 0.00019 0.00027 0.00040 0.00057 0.00081 0.00113 0.00157
 6.2  0.00013 0.00020 0.00029 0.00043 0.00063 0.00090 0.00128 0.00179 0.00248
 6.4  0.00021 0.00031 0.00047 0.00068 0.00100 0.00143 0.00202 0.00283 0.00392
 6.6  0.00033 0.00050 0.00074 0.00108 0.00158 0.00226 0.00320 0.00448 0.00620
 6.8  0.00052 0.00079 0.00117 0.00172 0.00251 0.00357 0.00507 0.00708 0.00979
 7.0  0.00083 0.00125 0.00186 0.00272 0.00397 0.00565 0.00801 0.01117 0.01543
 7.2  0.00131 0.00197 0.00294 0.00430 0.00627 0.00893 0.01263 0.01759 0.02424
 7.4  0.00208 0.00313 0.00465 0.00680 0.00990 0.01407 0.01987 0.02759 0.03788
 7.6  0.00329 0.00494 0.00735 0.01074 0.01561 0.02212 0.03113 0.04304 0.05874
 7.8  0.00520 0.00781 0.01160 0.01692 0.02451 0.03461 0.04846 0.06654 0.09000
 8.0  0.00822 0.01233 0.01826 0.02655 0.03830 0.05377 0.07468 0.10150 0.13551
 8.2  0.01297 0.01940 0.02863 0.04143 0.05936 0.08262 0.11341 0.15186 0.19900
 8.4  0.02040 0.03040 0.04463 0.06411 0.09093 0.12491 0.16856 0.22104 0.28251
 8.6  0.03195 0.04733 0.06894 0.09793 0.13684 0.18449 0.24318 0.31022 0.38426
 8.8  0.04970 0.07300 0.10503 0.14680 0.20080 0.26392 0.33742 0.41616 0.49725
 9.0  0.07655 0.11096 0.15683 0.21427 0.28480 0.36235 0.44663 0.53045 0.61052
 9.2  0.11612 0.16514 0.22767 0.30178 0.38692 0.47386 0.56124 0.64164 0.71301
 9.4  0.17233 0.23867 0.31843 0.40653 0.50006 0.58804 0.66968 0.73943 0.79747
 9.6  0.24812 0.33193 0.42544 0.52053 0.61319 0.69347 0.76265 0.81810 0.86189
 9.8  0.34341 0.44055 0.53992 0.63244 0.71530 0.78192 0.83586 0.87697 0.90818
10.0  0.45323 0.55517 0.65034 0.73169 0.79928 0.85036 0.88976 0.91868 0.94003
10.2  0.56780 0.66421 0.74670 0.81210 0.86322 0.90006 0.92749 0.94710 0.96131
10.4  0.67555 0.75816 0.82369 0.87261 0.90911 0.93453 0.95299 0.96596 0.97523
10.6  0.76744 0.83246 0.88102 0.91566 0.94066 0.95767 0.96982 0.97825 0.98423
10.8  0.83949 0.88732 0.92148 0.94507 0.96172 0.97287 0.98074 0.98616 0.98999
11.0  0.89235 0.92582 0.94898 0.96463 0.97550 0.98271 0.98776 0.99123 0.99366
11.2  0.92927 0.95188 0.96719 0.97739 0.98440 0.98902 0.99224 0.99445 0.99599
11.4  0.95417 0.96909 0.97904 0.98561 0.99010 0.99304 0.99509 0.99649 0.99747
11.6  0.97059 0.98027 0.98667 0.99087 0.99373 0.99560 0.99690 0.99778 0.99840
11.8  0.98124 0.98746 0.99155 0.99422 0.99604 0.99722 0.99804 0.99860 0.99899
12.0  0.98808 0.99205 0.99465 0.99635 0.99750 0.99824 0.99876 0.99912 0.99936
12.2  0.99245 0.99497 0.99662 0.99769 0.99842 0.99889 0.99922 0.99944 0.99960
12.4  0.99522 0.99682 0.99786 0.99854 0.99900 0.99930 0.99951 0.99965 0.99975
12.6  0.99698 0.99799 0.99865 0.99908 0.99937 0.99956 0.99969 0.99978 0.99984
12.8  0.99809 0.99873 0.99915 0.99942 0.99960 0.99972 0.99980 0.99986 0.99990
13.0  0.99880 0.99920 0.99946 0.99963 0.99975 0.99982 0.99988 0.99991 0.99994
STOP —
```

Table 20. Program Listing of NH3PH.

```
.R PIP
*TT:=NH3PH.FOR
        IMPLICIT REAL*8(R-Z)
        DIMENSION QI(9),QW(9),Z(9),M(9)
        DATA QI/1.374,1.479,1.570,1.652,1.710,1.774,1.820,1.849,1.862/
        DATA QW/14.9435,14.7338,14.5346,14.3463,14.1669,13.9965,
        * 13.8330,13.6801,13.5348/
        DO 100 I=1,9
100     M(I)=5*(I-1)
        TYPE 110,(M(I),I=1,9)
110     FORMAT (X,'TEMP,C:',9(I2,6X))
        TYPE 120
120     FORMAT (X,'PH')
        DO 130 K=1,41
        PH=5.+.2*(K-1)
        DO 140 I=1,9
        R=(10.**(PH+5.-QW(I)))/QI(I)
140     Z(I)=R/(1.+R)
        TYPE 150,PH,(Z(I),I=1,9)
150     FORMAT (X,F4.1,2X,9(F7.5,X))
130     CONTINUE
        END
```

Table 21. A Run of NO2; Showing the Proportions of Nitrite and Nitrous Acid to Their Sum, as a Function of pH.

```
.RUN NO2

ENTER HNO2 DISSOCIATION PK:3.37

ENTER PH LOW & HIGH:3.0,8.0

PH     HNO2/TOT   NO2/TOT
  3.0  0.70098    0.29902
  3.2  0.59663    0.40337
  3.4  0.48274    0.51726
  3.6  0.37061    0.62939
  3.8  0.27089    0.72911
  4.0  0.18990    0.81010
  4.2  0.12885    0.87115
  4.4  0.08536    0.91464
  4.6  0.05561    0.94439
  4.8  0.03582    0.96418
  5.0  0.02291    0.97709
  5.2  0.01458    0.98542
  5.4  0.00925    0.99075
  5.6  0.00585    0.99415
  5.8  0.00370    0.99630
  6.0  0.00234    0.99766
  6.2  0.00148    0.99852
  6.4  0.00093    0.99907
  6.6  0.00059    0.99941
  6.8  0.00037    0.99963
  7.0  0.00023    0.99977
  7.2  0.00015    0.99985
  7.4  0.00009    0.99991
  7.6  0.00006    0.99994
  7.8  0.00004    0.99996
  8.0  0.00002    0.99998
STOP —
```

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Table 22. Program Listing of NO2.

```
.R PIP
*TT:=NO2.FOR
        IMPLICIT REAL*8 (A-G,R-Z)
        TYPE 80
80      FORMAT(X,'ENTER HNO2 DISSOCIATION PK:',$)
        ACCEPT 85,QI
85      FORMAT(F7.3)
        TYPE 90
90      FORMAT(X,'ENTER PH LOW & HIGH:',$)
        ACCEPT 95,PH1,PH2
95      FORMAT(2(F6.2))
        PH=PH1
        TYPE 120
120     FORMAT(X,'PH     HNO2/TOT  NO2/TOT')
200     X1=10.**(QI-PH)
        R=X1/(1.+X1)
        R2=1.-R
        TYPE 600,PH,R,R2
600     FORMAT(X,F5.1,2X,F7.5,3X,F7.5)
        PH=PH+.2
        IF (PH.GT.PH2) GOTO 700
        GOTO 200
700     END
```

Since we can only measure total ammonia, we need the chart created by NH3PH to tell us the proportion of toxic un-ionized ammonia (see Colt and Tchobanoglous, 1976, and Robinette, 1976, for documentation of un-ionized ammonia toxicity). As shown in Table 13, ammonia shifts from relatively benign NH_4^+ to toxic NH_3 as pH rises above 8, well within the pH range of "young" photosynthetically active ponds. Whenever the chart has indicated that un-ionized ammonia levels are above 1 mg/l, fish growth appears harmed (see discussion of Experiment #2).

Before making a similar analysis for nitrite, high concentrations of nitrite appeared to have little effect on fish growth during the last part of Experiment #2 in Pond H because low pH during that period was postulated to force nitrite into nitrous acid, which perhaps was less toxic. However, as a run from NO2 shows, nitrite doesn't begin shifting to nitrous acid in significant quantities until pH drops below 4, well out of the range of pH observed in Pond H.

Thus, the inhibition of the high nitrite levels in Pond H requires an alternative hypothesis and further research.

D. DATA CONVERSION PROGRAMS

1. Determining Carbon Dioxide from pH and Alkalinity

When the carbonic acid/carbon dioxide/bicarbonate/carbonate system is in equilibrium, carbon dioxide can be predicted from the more easily measured parameters of pH and carbonate alkalinity. Though biologically active systems are seldom in chemical equilibrium because energy is constantly being captured and released in chemical bonds, the kinetics of the carbonate system are so rapid that real concentrations should not stray too far from theoretical equilibrium (see Riley and Skirrow, 1965, pp. 253-266). It is important to note that the chemical equilibrium referred to here does not imply equilibrium with the carbon dioxide in the atmosphere.

The equation below defines the equilibrium concentration of carbon dioxide as a function of carbonate alkalinity and hydrogen ion activity:

$$(CO_2) = \frac{(CA)*a_H}{K'_1\left[1+2K'_2/a_H\right]}$$

where CA = carbonate alkalinity

K'_1 and K'_2 = first and second apparent dissociation constants of carbonic acid

a_H = hydrogen ion activity

Because hydrogen ion activity virtually equals hydrogen concentration in dilute freshwater solutions, a_H 10^{-pH}. Likewise, the stochiometric literature lists the dissociation constants in their pK form, as a function of temperature. The equation for carbon dioxide therefore becomes:

$$(CO_2) = \frac{(CA)*10^{-pH}}{10^{-pK'1}\left[1+2(10^{(pH-pK'2)})\right]}$$

where pK'_1 and $pK'_2 = f(\text{temperature})$

Two programs are based on the latter equation, CO2T and CO2PH. CO2T lists the factor one multiplies by carbonate alkalinity to obtain carbon dioxide concentration. Temperature and pH determine the factor, so a table of factors is generated. CO2PH lists carbon dioxide as a function of pH after the user types in carbonate alkalinity, temperature and a pH range and increment.

Table 23. A Run of CO2T.

```
.RUN CO2T

TO GET MG CO2/L, MULTIPLY THE RELEVANT FACTOR BELOW BY ALKALINITY
EXPRESSED IN MG CACO3 PER LITER.
ENTER PH MIN,MAX & INCREMENT (INCLUDE
ONE DECIMAL POINT):4.0,9.0,.1

PH  TEMP: 05        10       15       20        25       30
 4.0      145.698 129.853 115.732 105.549   98.504   94.070
 4.1      115.732 103.146  91.929  83.840   78.244   74.723
 4.2       91.929  81.932  73.022  66.597   62.152   59.354
 4.3       73.022  65.081  58.003  52.900   49.369   47.147
 4.4       58.003  51.695  46.074  42.020   39.215   37.450
 4.5       46.074  41.063  36.598  33.377   31.150   29.748
 4.6       36.598  32.618  29.070  26.513   24.743   23.629
 4.7       29.070  25.900  23.091  21.060   19.654   18.769
 4.8       23.091  20.580  18.342  16.728   15.612   14.909
 4.9       18.342  16.347  14.570  13.288   12.401   11.843
 5.0       14.570  12.985  11.573  10.555    9.850    9.407
 5.1       11.573  10.315   9.193   8.384    7.824    7.472
 5.2        9.193   8.193   7.302   6.660    6.215    5.935
 5.3        7.302   6.508   5.800   5.290    4.937    4.715
 5.4        5.800   5.169   4.607   4.202    3.921    3.745
 5.5        4.607   4.106   3.660   3.338    3.115    2.975
 5.6        3.660   3.262   2.907   2.651    2.474    2.363
 5.7        2.907   2.591   2.309   2.106    1.965    1.877
 5.8        2.309   2.058   1.834   1.673    1.561    1.491
 5.9        1.834   1.635   1.457   1.329    1.240    1.184
 6.0        1.457   1.298   1.157   1.055    0.985    0.941
 6.1        1.157   1.031   0.919   0.838    0.782    0.747
 6.2        0.919   0.819   0.730   0.666    0.621    0.593
 6.3        0.730   0.651   0.580   0.529    0.494    0.471
 6.4        0.580   0.517   0.461   0.420    0.392    0.374
 6.5        0.461   0.411   0.366   0.334    0.311    0.297
 6.6        0.366   0.326   0.291   0.265    0.247    0.236
 6.7        0.291   0.259   0.231   0.211    0.196    0.188
 6.8        0.231   0.206   0.183   0.167    0.156    0.149
 6.9        0.183   0.163   0.146   0.133    0.124    0.118
 7.0        0.146   0.130   0.116   0.105    0.098    0.094
 7.1        0.116   0.103   0.092   0.084    0.078    0.075
 7.2        0.092   0.082   0.073   0.067    0.062    0.059
 7.3        0.073   0.065   0.058   0.053    0.049    0.047
 7.4        0.058   0.052   0.046   0.042    0.039    0.037
 7.5        0.046   0.041   0.037   0.033    0.031    0.030
 7.6        0.037   0.033   0.029   0.026    0.025    0.024
 7.7        0.029   0.026   0.023   0.021    0.020    0.019
 7.8        0.023   0.020   0.018   0.017    0.016    0.015
 7.9        0.018   0.016   0.014   0.013    0.012    0.012
 8.0        0.014   0.013   0.011   0.010    0.010    0.009
 8.1        0.011   0.010   0.009   0.008    0.008    0.007
 8.2        0.009   0.008   0.007   0.007    0.006    0.006
 8.3        0.007   0.006   0.006   0.005    0.005    0.005
 8.4        0.006   0.005   0.005   0.004    0.004    0.004
 8.5        0.005   0.004   0.004   0.003    0.003    0.003
 8.6        0.004   0.003   0.003   0.003    0.002    0.002
 8.7        0.003   0.003   0.002   0.002    0.002    0.002
 8.8        0.002   0.002   0.002   0.002    0.001    0.001
 8.9        0.002   0.002   0.001   0.001    0.001    0.001
 9.0        0.001   0.001   0.001   0.001    0.001    0.001
 STOP --
```

Table 24. Program Listing of CO2T.

```
.R PIP
*TT:=CO2T.FOR
        REAL*8 BASE1,BASE2
        DIMENSION TK1(6),TK2(6),CO2(6)
        DATA TK1/6.52,6.47,6.42,6.38,6.35,6.33/
        DATA TK2/10.55,10.49,10.43,10.38,10.33,10.29/
        TYPE 100
100     FORMAT(X,'TO GET MG CO2/L, MULTIPLY THE RELEVANT FACTOR
        * BELOW BY ALKALINITY')
        TYPE 110
110     FORMAT(X,'EXPRESSED IN MG CACO3 PER LITER.')
        TYPE 120
120     FORMAT(X,'ENTER PH MIN,MAX & INCREMENT (INCLUDE')
        TYPE 121
121     FORMAT(X,'ONE DECIMAL POINT):',$)
        ACCEPT 125,PHMIN,PHMAX,PHINC
125     FORMAT(3(F5.1))
        ALK=.44
        PH=PHMIN
        TYPE 150
150     FORMAT(X,'PH  TEMP: 05',6X,'10',6X,'15',6X,'20',
        * 6X,'25',6X,'30')
200     CONTINUE
        DO 500 I=1,6
        BASE1=1.+((2.*10.**(-TK2(I)))/10.**(-PH))
        BASE2=BASE1*10.**(-TK1(I))
        CO2(I)=(ALK*10.**(-PH))/BASE2
500     CONTINUE
        TYPE 250,PH,(CO2(I),I=1,6)
250     FORMAT(X,F4.1,5X,6(F7.3,X))
        IF (PH.GE.PHMAX) GOTO 300
        PH=PH+PHINC
        GOTO 200
300     END
```

Table 25. A Run of CO2PH.

```
.RUN CO2PH

ENTER ALKALINITY IN MG CA%_O3 PER '_ITER (PROGRAM WILL
CONVERT TO MG CO2/L BY MULTIPLY'_NG BY .44):40.0

ENTER PH MIN,MAX & INCREMENT, (INCLUDE
ONE DECIMAL P%INT):4.0,1%..0,.2

ENTER TEMPERATURE, IN DEGREES CENTIGRADE (MUST BE A
MULTIPLE OF 5 NO G%EATER THAN 30):25

PH        CO2              CO2/CT
 4.00     3940.1442871   0.9955530
 4.20     2486.0617676   0.9929702
 4.40     1568.5985107   0.9889043
 4.60      989.7178955   0.9825279
 4.80      624.4684448   0.9725887
 5.00      394.0117493   0.9572412
 5.20      248.6034546   0.9338852
 5.40      156.8569794   0.8991155
 5.60       98.9686661   0.8490161
 5.80       62.4436722   0.7801201
 6.00       39.3979721   0.6912171
 6.20       24.8570709   0.5854636
 6.40       15.6824045   0.4711920
 6.60        9.8935785   0.3598505
 6.80        6.2410655   0.2617779
 7.00        3.9364893   0.1827823
 7.20        2.4824021   0.1236108
 7.40        1.5649362   0.0816562
 7.60        0.9860554   0.0530535
 7.80        0.6208123   0.0340716
 8.00        0.3903669   0.0216987
 8.20        0.2449764   0.0137280
 8.40        0.1532602   0.0086328
 8.60        0.0954195   0.0053923
 8.80        0.0589673   0.0033392
 9.00        0.0360313   0.0020431
 9.20        0.0216510   0.0012287
 9.40        0.0127016   0.0007212
 9.60        0.0072116   0.0004096
 9.80        0.0039270   0.0002231
10.00        0.0020358   0.0001157
10.20        0.0010014   0.0000569
10.40        0.0004683   0.0000266
10.60        0.0002095   0.0000119
10.80        0.0000905   0.0000051
11.00        0.0000381   0.0000022
11.20        0.0000157   0.0000009
STOP —
```

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Table 26. Program Listing of CO2PH.

```
.R PIP
*TT:=CO2PH.FOR
        REAL*8 BASE1,BASE2
        DIMENSION TK1(6),TK2(6)
        DATA TK1/6.52,6.47,6.42,6.38,6.35,6.33/
        DATA TK2/10.55,10.49,10.43,10.38,10.33,10.29/
        TYPE 100
100     FORMAT(X,'ENTER ALKALINITY IN MG CACO3 PER LITER (PROGRAM WILL')
        TYPE 101
101     FORMAT(X,'CONVERT TO MG CO2/L BY MULTIPLYING BY .44):',$)
        ACCEPT 110,ALK
110     FORMAT(F10.3)
        TYPE 120
120     FORMAT(X,'ENTER PH MIN,MAX & INCREMENT (INCLUDE')
        TYPE 121
121     FORMAT(X,'ONE DECIMAL POINT):',$)
        ACCEPT 125,PHMIN,PHMAX,PHINC
125     FORMAT(3(F5.1))
        TYPE 140
140     FORMAT(X,'ENTER TEMPERATURE, IN DEGREES CENTIGRADE (MUST BE A')
        TYPE 141
141     FORMAT(X,'MULTIPLE OF 5 NO GREATER THAN 30):',$)
        ACCEPT 145,ITEMP
145     FORMAT(I2)
        I=ITEMP/5
        ALK=ALK*.44
        PH=PHMIN
        TYPE 150
150     FORMAT(X,'PH        CO2             CO2/CT')
200     CONTINUE
        BASE1=1.+((2.*10.**(-TK2(I)))/10.**(-PH))
        BASE2=BASE1*10.**(-TK1(I))
        CO2=(ALK*10.**(-PH))/BASE2
        FCO2=CO2/(CO2+ALK)
        TYPE 250,PH,CO2,FCO2
250     FORMAT(X,F5.2,4X,F12.7,2X,F9.7)
        IF (PH.GE.PHMAX) GOTO 300
        PH=PH+PHINC
        GOTO 200
300     END
```

2. Deriving Algae Biovolumes from Speciated Algal Cell Counts

In the algal cell counts, the basic unit counted (either a cell or a colony) varied in volume between species by as much as 300 times. The cell counts can therefore give a very misleading picture of the total volume and biomass of algae.

BIOV was devised to translate the speciated cell counts into total biovolumes. Information in Tables 27 and 28 determine the volumes of each of the algae species counted in Experiment #2. Similar tables were drawn up for Experiment #3.

Table 27. Computing Algae Volumes.

Code Name	Algal Species	Analogous Shape	Dimensions #(aμ x bμ)	Volume (cubic microns)
SC.2	*Scenedesmus quadricauda*, 2 cells	p. spheroid	2(1.25 x 3.5)	94
SC.3	*Scenedesmus quadricauda*, 3 cells	p. spheroid	3(1.25 x 3.5)	141
SC.4	*Scenedesmus quadricauda*, 4 cells	p. spheroid	4(1.25 x 3.5)	188
AN.F	*Ankistrodesmus falcatus*	cylinder	1.5 x 15	106
AN.B	*Ankistrodesmus brauni*	p. spheroid	6(1.5 x 2)	113
CH.1	*Chlorella #1*	sphere	2.6	74
CH.2	*Chlorella* #2	sphere	1.2	7
SP.5	*Sphaerocystis schroeteri*	sphere	7.5	1,770
MC.P	*Micractinium pusillum*	sphere	16(2.0)	536
GO.R	*Golenkinia radiata*	sphere	5	524
RADI	*Radiococcus*	sphere	4(2.5)	262
VOLV	*Volvox*	spherical shell	15 x .75	2,100

Table 28. Volume Formulas.

Shape	Formula	Variable Definitions
Sphere	$(4/3)\pi a^3$	a = radius
Oblate Spheroid (disk)	$(4/3)\pi ab^2$	a = shortest length, center-to-edge
Prolate Spheroid (cigar)	$(4/3)\pi a^2b$	b = longest length, center-to-edge
Cylinder	πa^2b	a = radius, b = height
Spherical Shell	$4\pi a^2b$	a = radius, b = shell thickness

The first part of a run of BIOV, plus the first section of the data file that BIOV draws upon, is shown in Tables 29 and 30.

Table 29. First Section of BIOV Run.

```
.RUN BIOV

'BIOV' CALCULATES ALGAL BIOVOLUMES FROM CELL COUNTS.
ALGAL CELL VOLUMES (IN CUBIC MICRONS) ASSUMED ARE:
SCENEDESMUS QUADRICAUDA, 2 CELL COLONY      94.CU.MIC.
   "            "      , 3 CELL COLONY    141.
   "            "      , 4 CELL COLONY    188.
ANKISTRODESMUS FALCATUS                   106.
ANKISTRODESMUS BRAUNI, 6 CELL COLONY      113.
CHLORELLA, LARGE SPECIES                   74.
CHLORELLA, SMALL SPECIES                    7.
SPHAEROCYSTIS SCHROETERI                 1770.
MICRACTINIUM PUSILLUM, 16 CELL COLONY     536.
GOLENKINIA RADIATA                        524.
RADIOCOCCUS SP., 4 CELL COLONY            262.
VOLVOX SP., MULTICELLULAR COLONY         2100.
THE DETAILS FOR THE DATA FILE THAT 'BIOV' DRAWS FROM
ARE.VERY IMPORTANT. THE CELL COUNTS FOR EACH CATEGORY
MUST BE ENTERED IN THE ORDER LISTED ABOVE. EACH DATA
ROW REPRESENTS A DIFFERENT DAY OF OBSERTVATIONS. EACH
COLUMN IS A CELL-COUNTING CATEGORY. CELL COUNTS MUST
BE IN UNITS OF 10E5. NUMBERS MUST HAVE A DECIMAL
POINT., AND NO MORE THAN TWO DECIMAL PLACES. ZEROES
DO NOT REQUIRE A DECIMAL POINT. IF ONLY THE FIRST FEW
ENTRIES IN A ROW HAVE NON-ZERO VALUES, THE REMAINING
ENTRY SPACES CAN BE SKIPPED WITH A 'RETURN.'
0,1.,0,3.22,4.1
IS AN ACCEPTABLE DATA ROW. 100 THOUSAND SCENEDESMUS
COLONIES AVERAGING 3 CELLS/COLONY,,322 THOU. ANKISTRO-
DESMUS FALCATUS CELLS AND 410E3 ANK. BRAUNI COLONIES
EXISTED IN A MILLILITER OF WATER IN THAT POND ON THAT
DAY.
NEW CHANGE: TYPE DATE IN FIRST COLUMN: 'MONTH#.DAY#'
*POND1L.DAT

DATE     TOTAL BIOVOLUME (10E7 CU.MICRONS)
 8.02           6.56
 8.03           8.26
 8.04          16.85
 8.05          12.89
 8.07          21.68
 8.08           6.61
 8.09           5.45
 8.10           7.40
 8.11           9.04
 8.12          13.83
```

Table 30. First Section of Data File BIOV Used in Run Shown.

```
*TT:=POND1L.DAT
08.02,00000,00.34,00000,04.20,00000,02.20,00000,000000,00000,00000,0,0,0
08.03,00000,00.25,00000,06.20,00000,01.80
08.04,00000,05.50,00000,06.00,00000,03.70
08.05,00000,00.15,00000,10.40,00.6,01.06,02.72
08.07,00000,01,00,00000,07.80,00.40,02.40,00.70,0,0,0,0,00.10
08.08,00000,00.50,00000,03.70,00.20,02.30,00.75
08.09,00000,00.40,00000,00.80,00000,02.90,00.09,0,0,0,0,00.09
08.10,00000,01.34,00000,01.25,00000,05.50,01.59,
08.11,00000,01.50,00000,00.50,00.13,04.75,00.05,0,0,0,0,00.13
08.12,00000,03.05,00000,00.20,00000,04.45,00.80.00.10,0,0,0,00.20
```

3. Calculating Solar Radiation Entering a Solar Pond from Daily Totals of Horizontal Radiation

SOLAR1, described in the May 23, 1978, progress report, was the first program written to calculate the total amount of solar radiation penetrating the sides of a solar-algae pond located in the solar courtyard. A long series of carefully timed and located solar radiation measurements taken in the solar courtyard allowed the refinement of SOLAR1. The new version, SOLAR2, differs from SOLAR1 in the following ways:

a. Transmittance-Absorptance Factor for Diffuse Light

Measurements of transmittance on cloudy days indicated that diffuse radiation should be explicitly modeled as light coming from all sections of the sky's hemisphere, rather than simplifying the model to an "average" angle of incidence for the incoming diffuse light. In the hemispherical model, the transmittance for each angle of incidence must be weighted by its respective solid angle, which can be visualized as a proportion of the total hemispherical area from which the light emanates. Table 31 breaks the angle of incidence into nine intervals, and calculates the resulting overall transmission factor.

Table 31. Calculating the Weighted Transmission for Diffuse Radiation.

Angle of Incidence	Weighted Area of Pond Angle	Respective $\tau\alpha$	Product
0 - 10	.135	.78	.105
10 - 20	.405	.76	.308
20 - 30	.666	.74	.483
30 - 40	.900	.71	.640
40 - 50	1.107	.65	.720
50 - 60	1.287	.54	.695
60 - 70	1.422	.41	.583
70 - 80	1.512	.22	.333
80 - 90	1.566	.00	.000
Average	1.00		.431

b. Radiation Penetration to the Pond's Top Surface

In SOLAR1, horizontal radiation was diminished by the double-walled acrylic lids year round. In SOLAR2, the lids are assumed to be in place only during the appropriate winter months. At other times of the year horizontal radiation is only diminished by reflection off the water's surface.

c. Reflected Solar Radiation

The major change in SOLAR1 involves the modeling of reflected sunlight. The "Sunlight Patterns Without, Chemistry Patterns Within" article in Appendix I , describes SOLAR2's method of modeling reflected radiation, as well as the radiation measurements upon which the new model is based. To summarize the new model of reflected radiation:

1) Reflected radiation (originating from diffuse light) increases the diffuse light entering the pond sides by 50%.

2) Reflected light originating from direct radiation is referenced to noon, September 30, 1978. At that time, this kind of reflected radiation was 46% of the direct radiation entering the pond sides.

3) On the other days of the year, and other times of the day, reflected radiation (from direct light) is adjusted from the September 30 standard of 46% by the following ratio:

$$\frac{\text{cosine of the sun's altitude at time in question}}{\text{cosine of the sun's altitude at noon on September 30, 1978}}$$

4) Radiation from the back wall (which far exceeds reflection from the marble chip ground cover at noon) is adjusted downwards at times other than noon by multiplying by the cosine of the sun's azimuth. An azimuth angle of zero degrees represents due south (and thus noon).

The results of SOLAR2 are listed in the "Patterns" article in the appendices. On a monthly basis, reflected radiation comprises 16% to 28% of the total radiation entering the pond. Reflection plays its largest role in the winter months, when the sun tracks across the sky in a low arc, enhancing the effectiveness of the back wall reflector.

E. MODELS WITH IMMEDIATE IMPLICATIONS FOR SOLAR-ALGAE POND MANAGEMENT

1. Simple Fish Growth and Food Conversion Efficiency Model

Even very simple models can yield intriguing results. This one assumes:

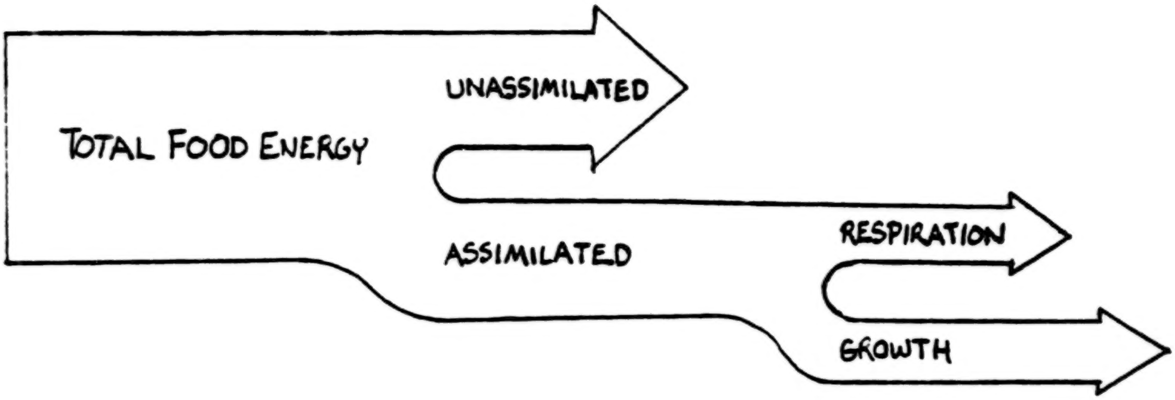
1) all fish classes and all feeding rates have the same assimilation efficiency;

2) respiration is proportional to body weight to the 0.8 power, so respiration per gram of body weight actually decreases as fish size increases (e.g., see Paloheimo and Dickie, 1966. Constant ranges from 0.7 - 0.85 depending on species.).

3) water quality is constant.

4) reproductive energy requirements are not considered for large fish (e.g., monosex hybrids).

Figure 13: Energy Pathways in Fish Growth Model:



The resulting table is of food conversion ratios (dry wt. food/ wet wt. growth). Quite simply, the bigger the fish and greater the feeding rate relative to biomass, the better (lower) the food conversion ratio. In the table %BW FED means percent of body weight fed daily. Weight is in grams.

Table 32. Food Conversion Ratio (Dry Wt. Feed/Wet Wt. Growth) as a Function of Fish Weight and Relative Feeding Rate.

```
XBW FED:  1        2        3        4        5        6        7        8        9
WEIGHT
  25.    7.004    1.235    0.968    0.874    0.826    0.796    0.777    0.763    0.752
  50.    3.182    1.116    0.917    0.842    0.803    0.778    0.762    0.750    0.741
  75.    2.469    1.062    0.892    0.826    0.791    0.769    0.755    0.744    0.736
 100.    2.151    1.029    0.877    0.816    0.784    0.764    0.750    0.740    0.732
 125.    1.964    1.006    0.865    0.809    0.778    0.759    0.746    0.737    0.729
 150.    1.838    0.989    0.857    0.803    0.774    0.756    0.743    0.734    0.727
 175.    1.747    0.975    0.850    0.799    0.771    0.753    0.741    0.732    0.726
 200.    1.677    0.964    0.844    0.795    0.768    0.751    0.739    0.731    0.724
 225.    1.621    0.955    0.839    0.792    0.766    0.749    0.738    0.729    0.723
 250.    1.575    0.946    0.835    0.789    0.763    0.747    0.736    0.728    0.722
 275.    1.537    0.939    0.832    0.786    0.762    0.746    0.735    0.727    0.721
 300.    1.504    0.933    0.828    0.784    0.760    0.745    0.734    0.726    0.720
 325.    1.475    0.927    0.825    0.782    0.758    0.743    0.733    0.725    0.720
 350.    1.450    0.922    0.823    0.780    0.757    0.742    0.732    0.725    0.719
 375.    1.428    0.918    0.820    0.779    0.756    0.741    0.731    0.724    0.718
 400.    1.408    0.914    0.818    0.777    0.755    0.740    0.731    0.723    0.718
 425.    1.389    0.910    0.816    0.776    0.754    0.740    0.730    0.723    0.717
 450.    1.373    0.906    0.814    0.775    0.753    0.739    0.729    0.722    0.717
STOP —
```

If true, this model has real implications for our culture strategy management (harvest fish at larger rather than smaller sizes). Experiments now in progress in the Ark are a good test of the model: it will let us compare varying size classes and weight-relative feeding rates (due to different biomasses receiving same absolute rate).

This model does have one glaring unrealistic aspect; it has no food satiation limits. Below, lines are drawn approximating this limit. The region under the curve doesn't exist (fish can't eat that much). Also, close to the limit (say, 80% of satiation) we might expect the assimilation efficiency to decrease (food passes through the gut too quickly).

Table 33. Fish Satiation Limits.

```
%BW FED:  1         2         3         4         5         6         7         8         9
WEIGHT
  25.     7.084     1.235     0.968     0.874     0.826     0.796     0.777     0.763     0.752
  50.     3.182     1.116     0.917     0.842     0.803     0.778     0.762     0.750     0.741
  75.     2.469     1.062     0.892     0.826     0.791     0.769     0.755     0.744     0.736
 100.     2.151     1.029     0.877     0.816     0.784     0.764     0.750     0.740     0.732
 125.     1.964     1.006     0.865     0.809     0.778     0.759     0.746     0.737     0.729
 150.     1.838     0.989     0.857     0.803     0.774     0.756     0.743     0.734     0.727
 175.     1.747     0.976     0.850     0.799     0.771     0.753     0.741     0.732     0.726
 200.     1.677     0.964     0.844     0.795     0.768     0.751     0.739     0.731     0.724
 225.     1.621     0.955     0.839     0.792     0.766     0.749     0.738     0.729     0.723
 250.     1.575     0.946     0.835     0.789     0.763     0.747     0.736     0.728     0.722
 275.     1.537     0.939     0.832     0.786     0.762     0.746     0.735     0.727     0.721
 300.     1.504     0.933     0.828     0.784     0.760     0.745     0.734     0.726     0.720
 325.     1.475     0.927     0.825     0.782     0.758     0.743     0.733     0.725     0.720
 350.     1.450     0.922     0.823     0.780     0.757     0.742     0.732     0.725     0.719
 375.     1.428     0.918     0.820     0.779     0.756     0.741     0.731     0.724     0.718
 400.     1.408     0.914     0.818     0.777     0.755     0.740     0.731     0.723     0.718
 425.     1.389     0.910     0.816     0.776     0.754     0.740     0.730     0.723     0.717
 450.     1.373     0.906     0.814     0.775     0.753     0.739     0.729     0.722     0.717
STOP --
```

UNREALISTIC REGION
DUE TO- SATIATION

One can't really tell from the output, but the internal calculations agree with each other and with reality. Respiration rates are based on Caulton's 1977 data for 25°C. Caloric value of trout chow was calculated from the nutrition tables in the National Research Council's 1977 booklet "Nutrient Requirements of Warmwater Fishes", and the caloric content of tilapia biomass was a compromise between Winberg (1971) and Meakins (1976). The energy assimilation efficiency of 50% matches the nitrogen assimilation efficiency calculated from Experiment #2. This is slightly lower than the efficiency of 60% for poultry eating the same feed (again, calculated from the nutrition tables). This agrees with the

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generalization that poultry have slightly better assimilation efficiencies, but also much higher respiration losses, than fish.

The program, surprisingly brief, is listed below (in FORTRAN).

Table 34. Listing of Simple Fish Growth Model.

```
.R PIP
*TT:=FIGRO.FOR
        DIMENSION P(9),C(9)
        DO 100 I=1,9
100     P(I)=I*.01
        TYPE 110,(I,I=1,9)
110     FORMAT(X,'%BW FED:',9(X,I2,5X))
        TYPE 120
120     FORMAT(X,'WEIGHT')
        DO 130 J=1,18
        W=25.*J
        DO 140 I=1,9
        F=W*P(I)*4140.   ! 4140 = CAL/GM FOOD
        U=F*.5           ! .5 = UNASSIM. FRAC.
        R=50.*16.3*((W/50.)**.8)
        *       ! 16.3 = RES: CAL/GM FISH;  .8 = RES. WT. EXP.
        G=(F-U-R)/1400. ! 1400 = CAL/GM WET FISH
140     C(I)=W*P(I)/G
        TYPE 150,W,(C(I),I=1,9)
150     FORMAT(X,F4.0,3X,9(F6.3,2X))
130     CONTINUE
        END
*
```

2. A Diurnal Model of Solar-Algae Ponds

The diurnal fluctuations of temperature, oxygen and pH in the solar ponds spring from a mixture of the pond's internal biology and external conditions. Figure 14 illustrates these fluctuations for one solar pond on August 18, 1978. Figure 15 shows the output of DAY2A, a System Dynamics model built to study these fluctuations. Given the external conditions on August 18, the model reproduces the pond's internal temperature and oxygen fluctuations quite precisely. The essence of the carbon dioxide and pH dynamics are also captured by the model, although duplication of the data is less precise. This is not surprising, given the intricacies of the pH/carbon system and a lack of consensus in the literature regarding critical relationships.

The model's variables can be divided into exogenous and endogenous categories; that is, externally derived and internally derived variables. The major sections of the model are described according to these categories below:

1) Exogenous Variables.

a) Sunlight. The model deduces the amount of sunlight entering the ponds from horizontal solar measurements, in a manner analogous to SOLAR2.

b) Air temperature. Day-time air temperatures in the solar courtyard are assumed to be slightly higher than temperatures recorded in a shaded weather box located on the north side of a concrete wall.

Figure 14: Computer Record of Solar-Algae Pond on August 18, 1978:

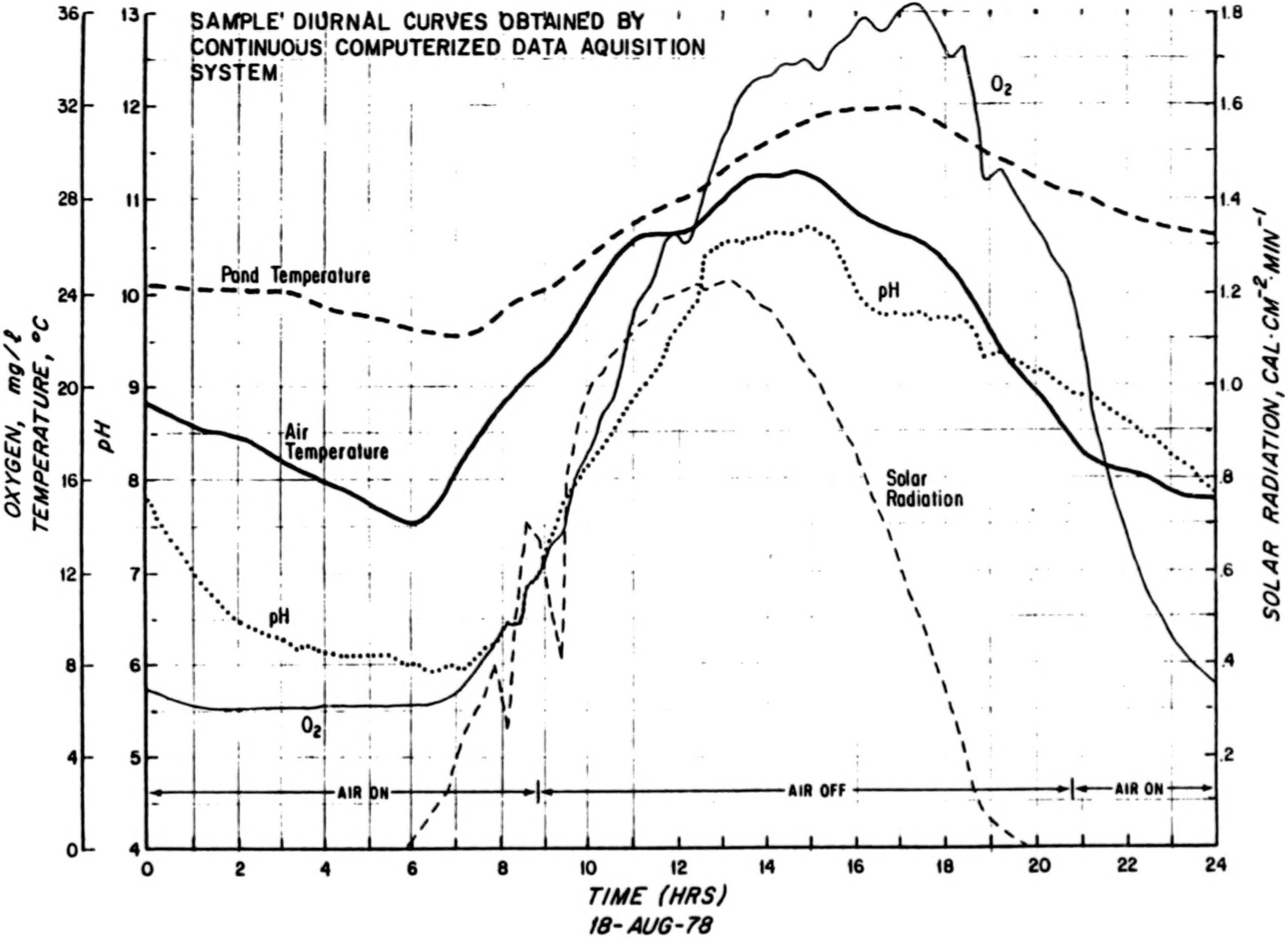
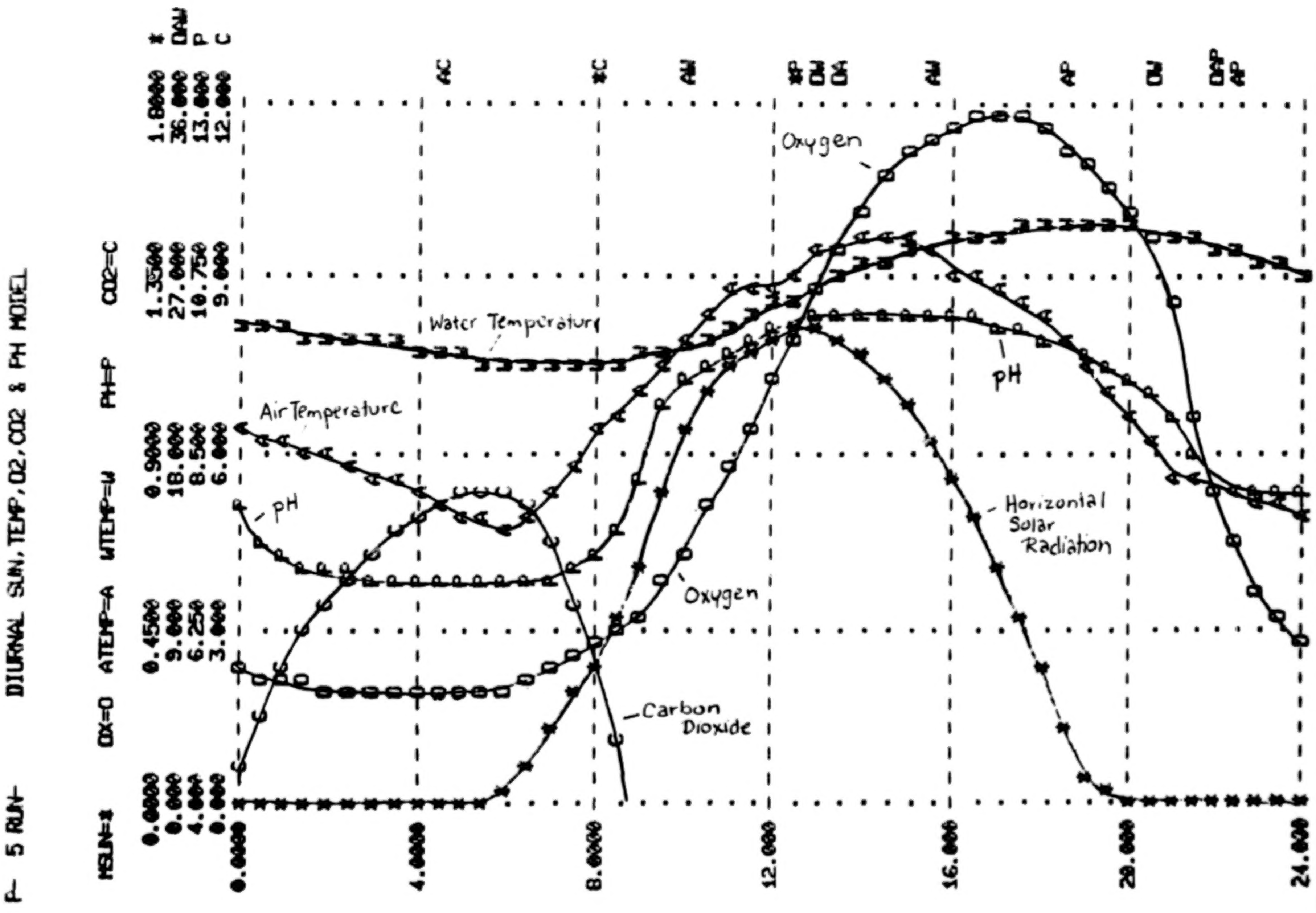


Figure 15: Computer Simulation of Solar-Algae Pond on August 18, 1978:



c) Aeration. From 7:45 PM to 8:45 AM, aeration increases the rates at which the dissolved gases (i.e., oxygen and carbon dioxide) approach equilibrium with the atmosphere.

2) Endogenous Variables.

a) Water temperature. Solar energy entering the pond represents a heat gain. The difference between internal and external temperatures, combined with standard engineering coefficients, determine heat loss. The net heat gain or loss is divided by the water column's thermal capacity to determine the change in internal temperature.

b) Oxygen. The life within the pond respires, consuming oxygen, at a relatively constant rate (photorespiration is not included here). Temperature affects respiration slightly, and if oxygen levels drop below 2 mg/1, respiration will decrease (this effect does not occur in the run shown). Incoming solar radiation, multiplied by an unvarying coefficient, determines net photosynthesis and oxygen production. The oxygen concentration tends toward a level in equilibrium with the atmosphere. The equilibrium concentration varies with water temperature. The rate of oxygen gain or loss in attempting to reach atmospheric equilibrium is a function of aeration and the difference between actual and equilibrium oxygen levels.

c) Carbon dioxide. Biologically, carbon dioxide mirrors oxygen. Photosynthesis depletes carbon dioxide and respiration produces it. Like oxygen and other dissolved gases, carbon dioxide tends toward an equilibrium with the atmosphere. Unlike most dissolved gases, carbon dioxide reacts with water molecules and hydroxyl ions in the boundary water layer, creating a bicarbonate gradient that enhances carbon dioxide transfer. This enhancement factor varies with pH, temperature and alkalinity (Quinn and Otto, 1971, and Emerson, Broecker and Schindler, 1973).

d) Bicarbonate. Under intense algal photosynthesis, carbon dioxide may be depleted. Bicarbonate ions can then act as a carbon source for the algae.

e) pH. pH is determined by the ratio of carbon dioxide to alkalinity. If carbon dioxide is depleted, then the ratio of bicarbonate ions to alkalinity defines pH.

The relationships described above are incremented through time in a "numerical simulation". Each of the variables shown in Figure 15 affects many variables not shown, and are in turn affected by many hidden variables. Figures 16, 17 and 18 reveal some of the variables and internal mechanisms in the solar radiation, temperature and oxygen sections on the August 18 run of DAY2A.

The model gains practical significance when it is modified to assess possible changes in solar-algae pond management. Figure 19 shows what happens if the aeration system didn't turn on: early morning oxygen levels plummet to anoxia and carbon dioxide concentrations soar. This would severely stress even the hardy tilapia.

In Figure 20 the model assumes the aeration operates until 8:45 AM, but does not turn back on in the evening. As shown, high afternoon oxygen

Figure 16: August 18 Computer Run Showing Major Variables in Oxygen Sector:

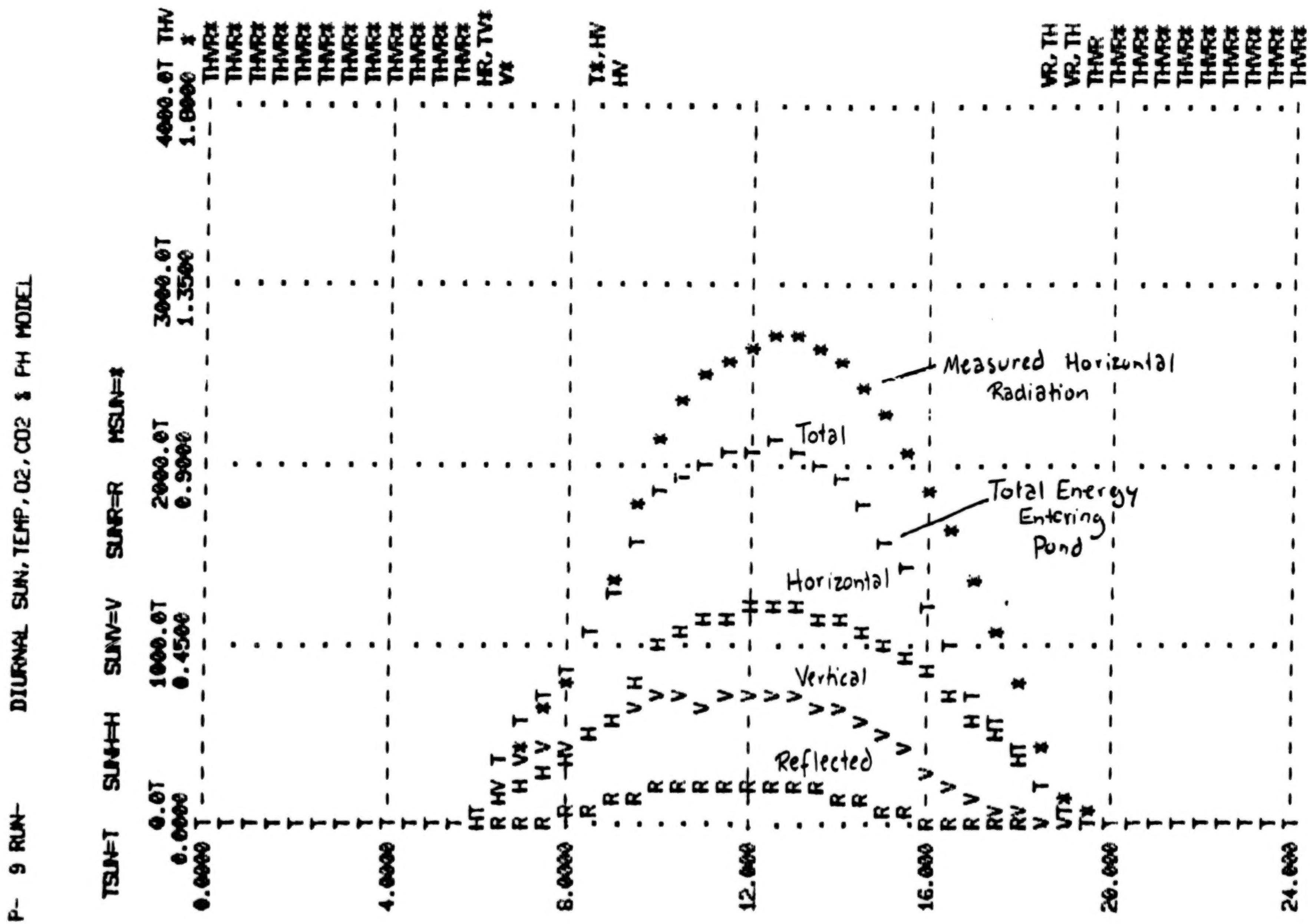


Figure 17: Computer Run Showing Major Variables in Solar Radiation Sector:

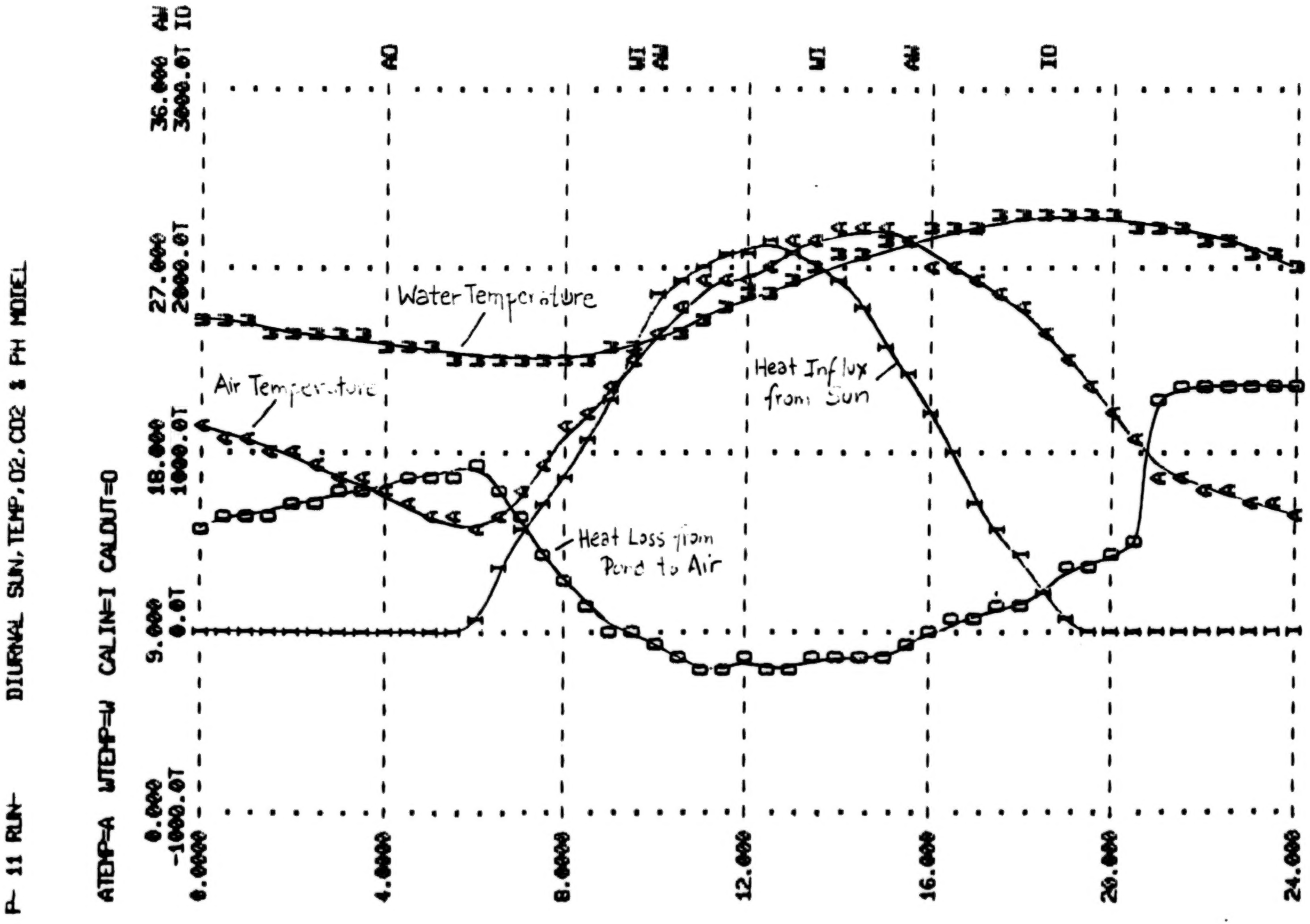


Figure 18: August 18 Computer Run Showing Major Variables in Temperature Sector:

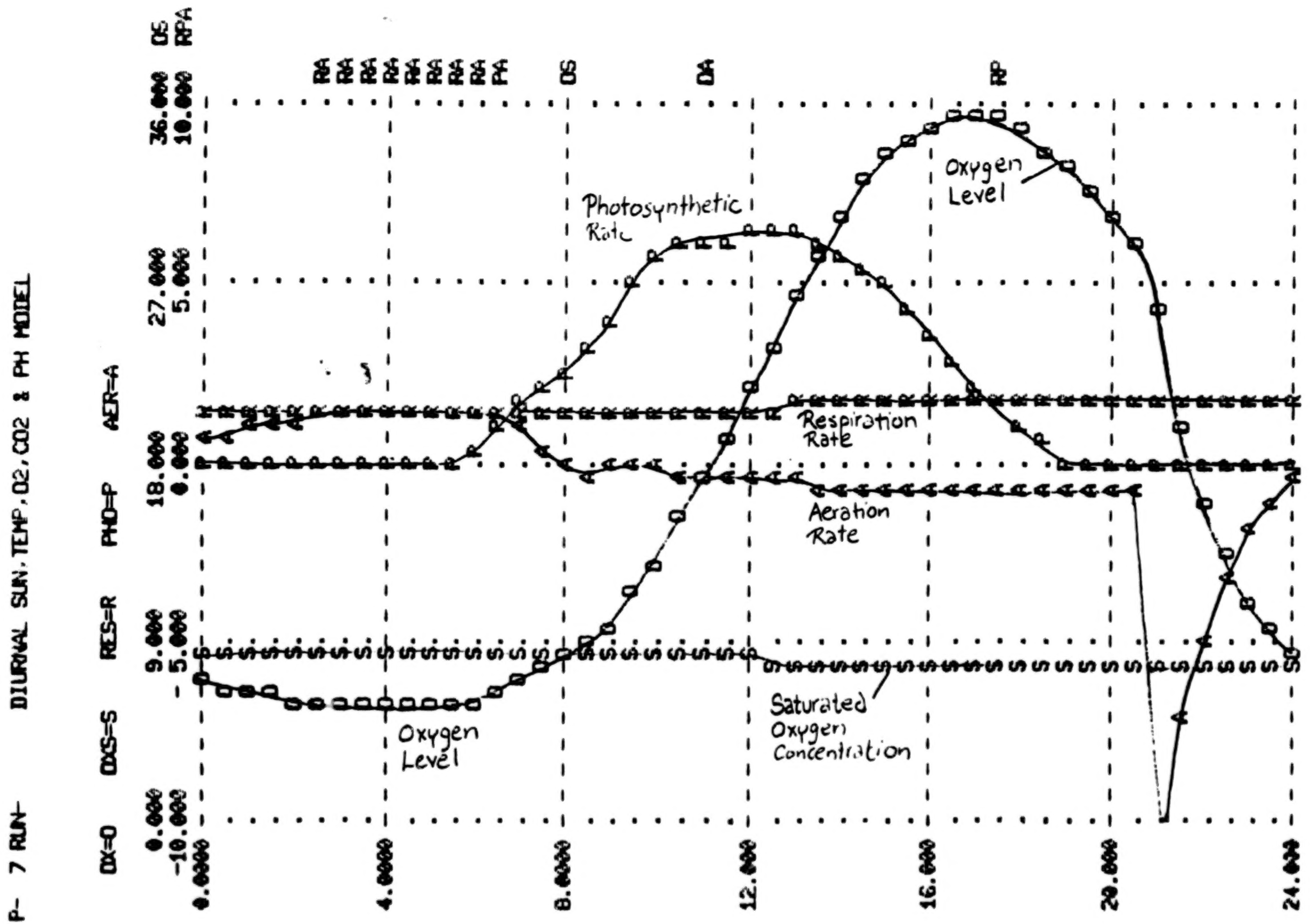


Figure 19: Computer Simulation of DAY2A with Aeration Off:

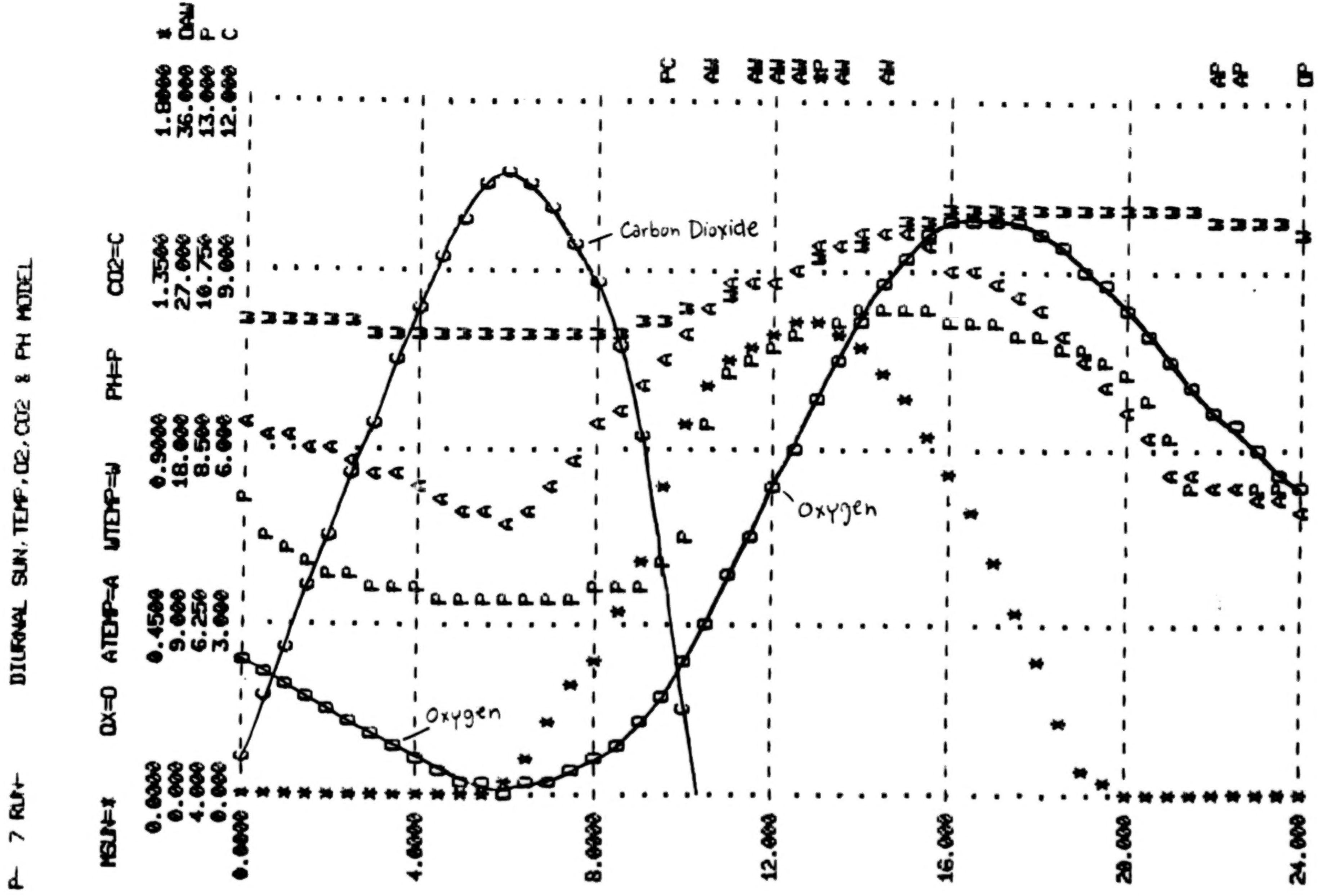
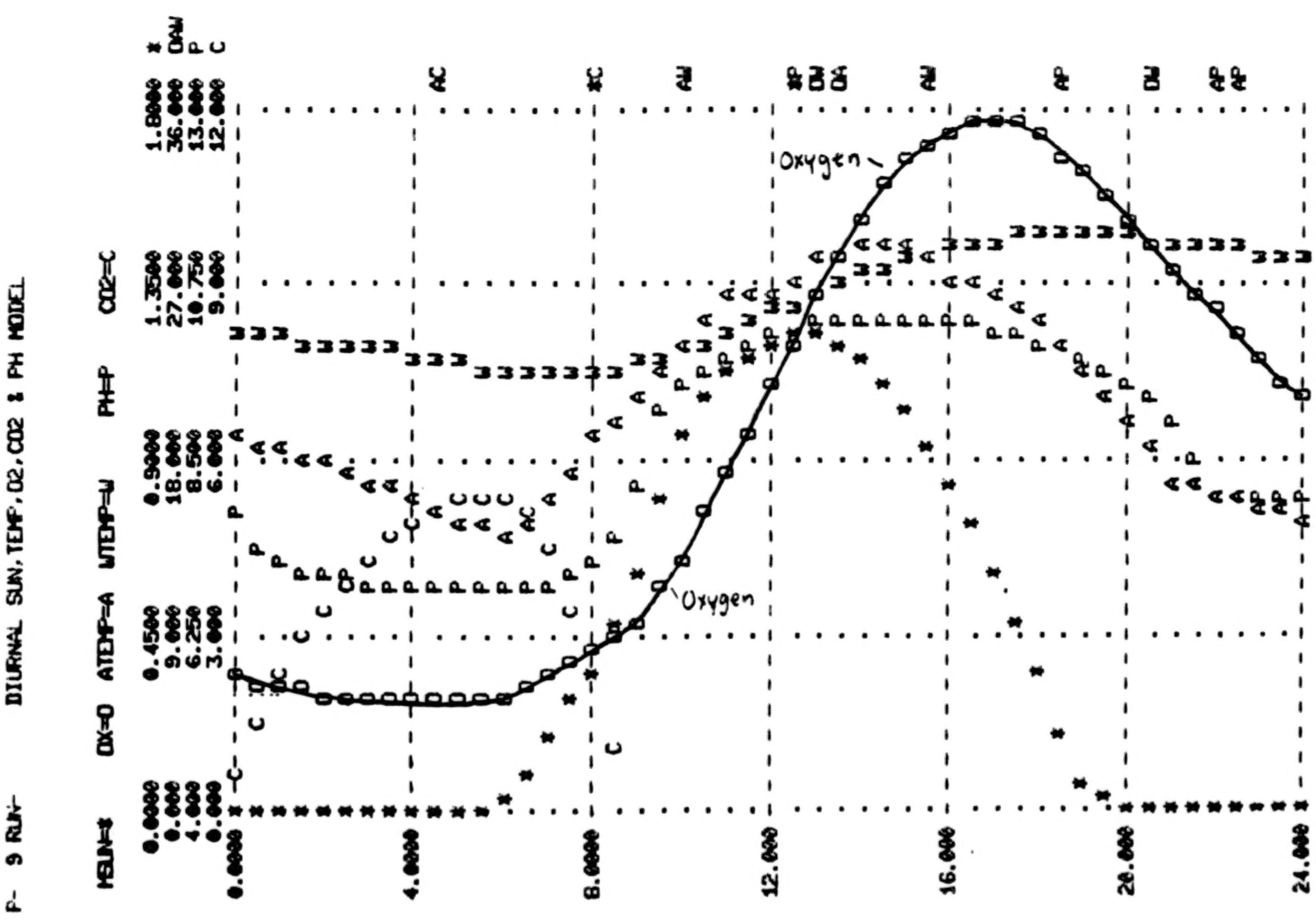


Figure 20: Computer Simulation of DAY2A With Aeration On In Morning but Off in Evening:



levels descend much more slowly. The evening aeration on August 18 was actually driving desirable oxygen out of the water. It appears that after a sunny day such as August 18, the aeration could remain off until 4:00 AM the next morning. This strategy of preserving oxygen overnight after days of strong photosynthesis not only cuts the energy costs of aeration, but also maintains higher night-time oxygen concentrations.

Table 35. DYNAMO Listing of the Diurnal System Dynamics Model DAY2A.

```
.R PIP
*TT:=DAY2A.DYN
*       DIURNAL SUN,TEMP,O2,CO2 & PH MODEL
NOTE
NOTE    SUNLIGHT SECTOR
NOTE
A       TSUN.K=SUNH.K+SUNV.K+SUNR.K
A       SUNH.K=AREAH*MSUNH.K
A       MSUNH.K=60*MSUN.K
A       MSUN.K=TABHL(MSUNT,TIME.K,0,24,1)
T       MSUNT=0/0/0/0/0/0/.02/.20/.35/.60/.98/1.12/1.20/1.22/
X       1.15/1.02/.85/.6/.35/.05/0/0/0/0/0
A       SUNV.K=(.5*TAV*AREAV*MSUNH.K)(DIFF+((1-DIFF)(VHRAT.K)(SHF.K)))
C       TAV=.45
C       DIFF=.20
A       VHRAT.K=CLIP(THEO.K,LIM,LIM,THEO.K)
C       LIM=2.5
A       THEO.K=COS(ALT.K)/SINALT
A       SINALT.K=SWITCH(.01,SIN(ALT.K),ALTD.K)
A       ALT.K=ALTD.K*.0174533
A       ALTD.K=TABHL(ALTDT,TIME.K,0,24,1)
T       ALTDT=0/0/0/0/0/0/10.3/21.5/32.6/43.2/52.5/59.2/61.1/
X       57.4/49.6/39.8/28.9/17.7/6.6/0/0/0/0/0/0
A       SHF.K=CLIP(1,COSAZ,12.1,TIME.K)
A       COSAZ.K=CLIP(0,COS(AZ.K),AZD,90)
A       AZ.K=AZD.K*.0174533
A       AZD.K=TABHL(AZDT,TIME.K,0,24,1)
T       AZDT=180/180/180/180/180/180/98.0/88.2/77.5/64.7/47.8/24.3/
X       0/33.0/54.0/69.3/81.2/88.5/101.3/180/180/180/180/180/180
A       SUNR.K=(SUNV.K)(REFF)(COS(ALT.K))(COSAZ.K)
C       REFF=.66
NOTE
L       SUN.K=SUN.J+(DT)(TSUNR.JK)
N       SUN=0
R       TSUNR.KL=TSUN.K
NOTE
NOTE    TEMPERATURE SECTOR
NOTE
L       WTEMP.K=WTEMP.J+(DT)(DELTEM.JK)
N       WTEMP=WTEMPI
C       WTEMPI=24.5
NOTE
R       DELTEM.KL=(CALIN.K-CALOUT.K)/WMASS
C       WMASS=2.3E6
A       CALIN.K=TSUN.K
A       CALOUT.K=(AREAV*TCV+AREAH*TCH.K)(WTEMP.K-(ATEMP.K+ADJ.K))
C       AREAV=6.6E4
C       AREAH=1.65E4
C       TCV=.3
A       TCH.K=TCH1+TCH2*Z1/Z.K
C       TCH1=1.5
C       TCH2=4
A       ATEMP.K=TABHL(ATEMPT,TIME.K,0,24,1)
T       ATEMPT=19.2/18.5/17.8/16.8/16.0/15.0/14.0/16.0/19.2/
X       21.0/23.5/26.2/26.6/28.0/29.0/29.0/27.3/26.5/25.3/22.2/
X       19.7/17.0/16.2/15.4/15.1
A       ADJ.K=TABHL(ADJT,TIME.K,0,24,4)
T       ADJT=0/0/.8/2.5/1.2/.2/0
```

```
NOTE
NOTE     OXYGEN SECTOR
NOTE
L        OX.K=OX.J+(DT)(PHO.JK-RES.JK+AER.JK)
N        OX=OXI
C        OXI=7
NOTE
R        PHO.KL=PHOT.K
A        PHOT.K=TSUN.K*PHOTF/(WMASS/1000)
C        PHOTF=.007
NOTE
R        RES.KL=RESP.K
A        RESP.K=RES20*RESTF.K*RESOF.K
C        RES20=1.2
A        RESTF.K=EXP((WTEMP-20)*LOGN(1.047))
A        RESOF.K=TABHL(RESOFT,OX.K,0,2,.4)
T        RESOFT=0/.5/.8/.9/.95/1.0
NOTE
R        AER.KL=DIF0X*(OXS.K-OX.K)/(DEPTH*Z.K)
C        DIF0X=.0828
C        DEPTH=145
A        Z.K=CLIP(Z1,Z3.K,AOFF,TIME.K)
A        Z3.K=CLIP(Z2,Z1,AON,TIME.K)
C        Z1=10E-4
C        Z2=200E-4
C        AOFF=6.8
C        AON=20.8
A        OXS.K=TABLE(OXST,WTEMP.K,10,35,1)
T        OXST=10.92/10.67/10.43/10.20/9.98/9.76/9.56/9.37/9.18/
X        9.01/8.84/8.68/8.53/8.38/8.25/8.11/7.99/7.86/7.75/7.64/
X        7.53/7.42/7.32/7.22/7.13/7.04
NOTE
L        RESPT.K=RESPT.J+(DT)(RES.JK)
N        RESPT=0
L        PHOTT.K=PHOTT.J+(DT)(PHO.JK)
N        PHOTT=0
NOTE
NOTE     CARBON DIOXIDE AND PH SECTOR
NOTE
NOTE     GENERAL VARIABLES
NOTE
C        ALK=17.6
C        CO2WT=1.375
A        ECO2R.K=CO2WT*RESP.K
A        ECO2P.K=CO2WT*PHOT.K
A        ECO2A.K=CO2A.K
NOTE
NOTE     CARBON DIOXIDE SECTOR
NOTE
L        CO2.K=CO2.J+(DT)(CO2RES.JK-CO2PHO.JK+CO2AER.JK)
N        CO2=CO2I
C        CO2I=.621
NOTE
R        CO2RES.KL=ECO2R.K*CO2SW.K
R        CO2PHO.KL=ECO2P.K*CO2SW.K
R        CO2AER.KL=ECO2A.K*CO2SW.K
A        CO2SW.K=TABHL(CO2SWT,CO2.K,0,.1,.1)
T        CO2SWT=0/1
```

```
NOTE
A       CO2A.K=EN.K*DIFCO2*(CO2SAT.K-CO2.K)/(DEPTH*Z.K)
A       EN.K=ENCF*ENTF.K
C       ENCF=1.0
A       ENTF.K=EXP((Z.K/460)*LOGN(ENPHF.K))
A       ENPHF.K=TABHL(ENPHFT,PH.K,5,11,1)
T       ENPHFT=1.03/1.14/1.22/1.23/1.24/1.24/1.24
C       DIFCO2=.0486
A       CO2SAT.K=CO2AIR*44*CO2SC.K
C       CO2AIR=320E-6
A       CO2SC.K=TABHL(CO2SCT,WTEMP.K,6,30,4)
T       CO2SCT=61.9/53.6/47.2/41.7/37.2/33.2/29.9
NOTE
NOTE    BICARBONATE SECTOR
NOTE
L       BIC.K=BIC.J+(DT)(BICRES.JK-BICPHO.JK+BICAER.JK)
N       BIC=ALK
NOTE
R       BICRES.KL=ECO2R.K*(1-CO2SW.K)
R       BICPHO.KL=ECO2P.K*(1-CO2SW.K)*BAR.K
R       BICAER.KL=ECO2A.K*(1-CO2SW.K)
NOTE
NOTE    PH SECTOR
NOTE
NOTE    PH DERIVED FROM CO2 & HCO3 AS PREDICTED ABOVE
NOTE
A       PH.K=CLIP(PHCO2.K,PHBIC.K,CO2.K,.100)
A       PHCO2.K=8.8-2.45-LCAR.K
A       LCAR.K=(LOGN(CO2NZ.K/ALK))/2.303
A       CO2NZ.K=MAX(CO2.K,.01)
A       PHBIC.K=TABHL(PHBICT,BAR.K,0,1,.05)
T       PHBICT=12.00/11.28/10.94/10.74/10.60/10.48/
X       10.36/10.26/10.16/10.08/9.98/
X       9.88/9.80/9.72/9.62/9.50/
X       9.38/9.24/9.00/8.68/8.00
A       BAR.K=BIC.K/ALK
NOTE
NOTE    PH DIRECTLY MEASURED, AND CO2 CALCULATED THEREOF
NOTE
A       MPH.K=TABHL(MPHT,TIME.K,0,24,1)
T       MPHT=7.8/7.0/6.5/6.3/6.15/6.1/
X       6.0/6.0/6.4/7.1/8.1/8.8/
X       9.7/10.5/10.6/10.7/10.0/9.75/
X       9.7/9.3/9.1/8.9/8.6/8.25/7.8
NOTE
A       MCO2.K=CO2MF.K*ALK
A       CO2MF.K=TABHL(CO2MFT,MPH.K,4,8.8,.2)
T       CO2MFT=224/141/89.1/56.2/35.5/
X       22.4/14.1/8.91/5.62/3.55/
X       2.24/1.41/.891/.562/.355/
X       .224/.141/.089/.056/.035/
X       .022/.014/.009/.005/.003
NOTE
A       MBIC.K=BICMF.K*ALK
A       BICMF.K=TABHL(BICMFT,MPH.K,6,13,.2)
T       BICMFT=1.000/1.000/1.000/1.000/.999/
X       .999/.999/.998/.996/.994/
X       .991/.985/.977/.964/.944/
X       .915/.871/.810/.729/.629/
X       .517/.403/.299/.212/.145/
X       .097/.063/.041/.026/.017/
X       .011/.007/.004/.003/.002/.001
```

```
NOTE
NOTE
NOTE    CONTROL SECTOR
NOTE
PRINT   TSUN,MSUN,OX,PHO,RES,AER,OXS,WTEMP,ATEMP,CALIN,CALOUT,
X       SUN,CO2,MCO2,BIC,MBIC,PH,MPH
SPEC    LENGTH=24/DT=.1/PLTPER=.5/PRTPER=0
PRINT   TSUN,SUNH,SUNV,SUNR,OXS,RES,PHO,AER,CALIN,CALOUT
PLOT    MSUN=*(0,1.8)/OX=O,ATEMP=A,WTEMP=W(0,36)
X       /PH=P(4,13)/CO2=C(0,12)
```

VIII. FUTURE COURSE OF RESEARCH

A. MODELING

The past year's experiments and modeling lay the groundwork for a comprehensive model of long-term fish growth in the solar-algae ponds. As now envisioned, the model will use nitrogen as the "common currency" that flows through the ecosystem (fish, algae, bacteria and detritus). The nitrogen flows illustrated in Figure 21 affect, and are affected by, oxygen, carbon dioxide, bicarbonate, hydrogen and hydroxyl ion concentrations. Table 7, previously listed, describes some of the ways nitrogen transformations affect the rest of the system, while Table 8 details how the rest of the system affects nitrogen flows. The first draft of the interwoven web of causality was diagrammed in the May, 1978, progress report. Figure 22 now details the nitrogen sector of the model with a DYNAMO flow diagram.

B. EXPERIMENTAL DESIGNS AND SEQUENCE FOR YEAR 3

Previous research focused upon monoculture production experiments with the tilapia, Sarotheradon aureus, using commercial feeds. In an attempt to improve productivity, the next year's research will follow four strategies:

1) fish species polyculture to optimally use all nutrient niches in the ponds,

2) use of fresh, live feeds,

3) ponds linked in series with water recirculation and trickle flow-through, and

Figure 21: Physical Flow of Nitrogen Through the Solar-Algae Pond Ecosystem:

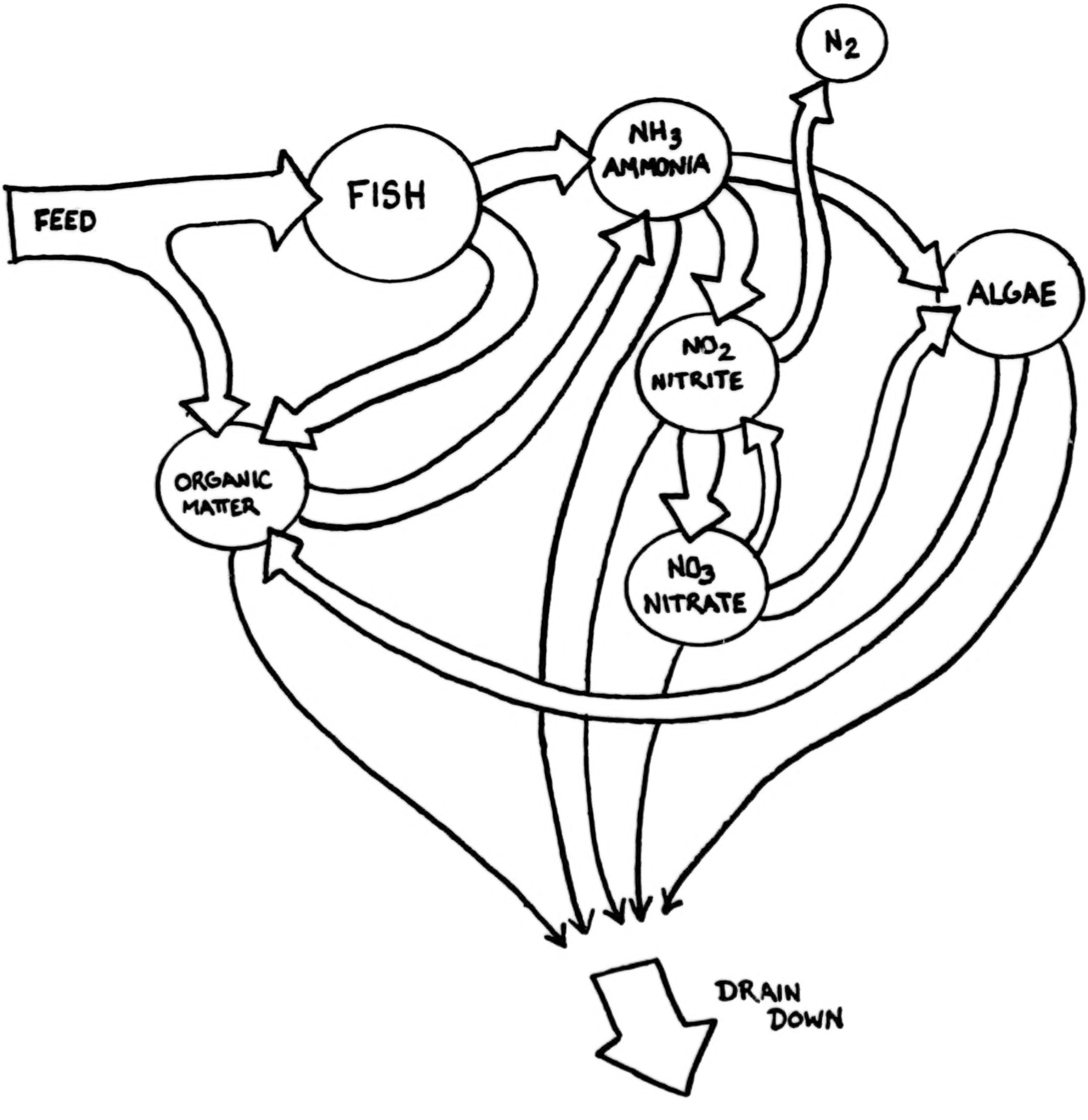
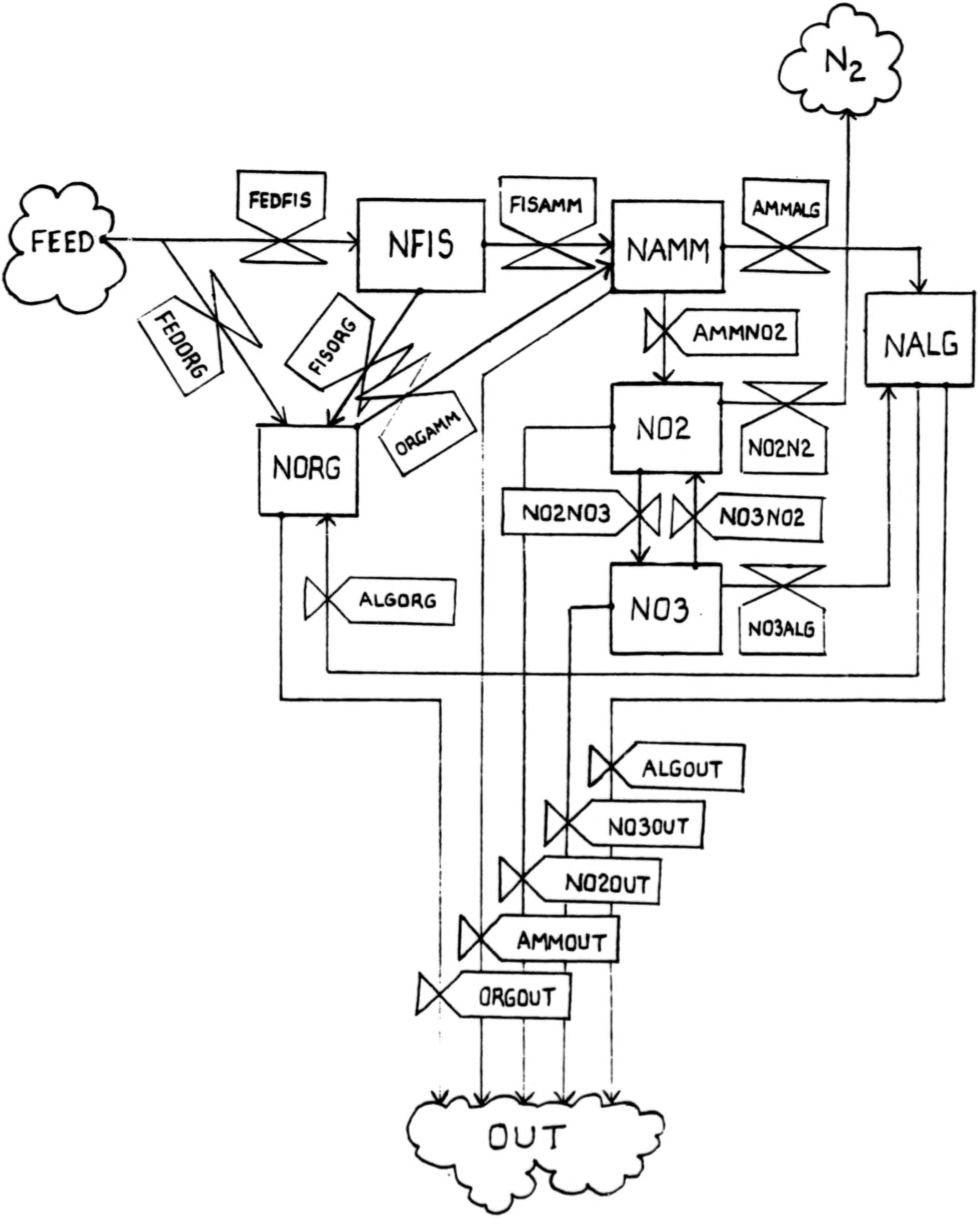


Figure 22: DYNAMO Flow Diagram of the Nitrogen Sector of the Comprehensive Solar Pond Aquaculture Model:



4) filtration techniques to improve water quality.

The following experiments will evaluate the impact of each of these strategies upon water chemistry and fish growth.

1. Early Summer 1979

    a. Growth and Water Chemistry Comparison Between Israeli Carp Monoculture, Tilapia Monoculture, and Carp/Tilapia Polyculture. Each species combination will have four replicates. Each replicate will have a different feeding regime.

        i. Trout Chow, 3% of fish biomass fed daily.

        ii. Rabbit Chow, 3% of fish biomass fed daily.

        iii. Rabbit Chow, 6% of fish biomass fed daily.

        iv. Rabbit Chow, 3% of fish biomass fed daily, plus earthworms (total nitrogen will equal 3% trout chow)

    b. Evaluation of Water Purification Techniques

        i. Recirculating sand filter for removal of senescent algae and solid wastes.

        ii. Recirculating hydroponics filter for removal of solid wastes and dissolved nitrogenous compounds.

        iii. Independent small sediment settling pond for removal of solid wastes.

        iv. Trickle flow-through "solar river" with rapid recirculation. The outflow will carry algal cells and solid wastes.

2. Late Summer and Fall 1979

    Carp/Tilapia/Bullhead Polyculture

Combinations will be determined after previous experiments' results are reviewed. Reference population will be the most productive regime of early summer trials. Half of these ponds will have best feed from the early summer trial and the other half will receive a mix of comfrey, worms and dry feed.

3. Winter 1979-1980

a. Refine water filtration techniques.

b. Test recirculating coupled ponds: one fed 1% trout chow and the other 5%. Water quality should be the same in each so feeding rates can be examined independent of water quality effects.

c. Examine carp/bullhead polyculture outside in solar courtyard ponds.

d. Comprehensively monitor thermal dynamics in ponds inside Ark and outdoors in solar courtyard.

e. Evaluate winter-time high density culture, raising tilapia fry to fingerling size inside Ark ponds.

4. Spring and Early Summer 1980

This will synthesize previous water purification, polyculture and feeding experiments. The comprehensive model of fish growth and water quality will determine management scheduling and fish densities.

The results from this series of experiments will test our mathematical models. The interaction of modeling and experimentation should allow us to reach an optimum mix of high fish productivity with low costs for solar-algae pond aquaculture.

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APPENDIX I

ARTICLES SUBMITTED FOR PUBLICATION, ACCEPTED FOR PUBLICATION OR PUBLISHED, WRITTEN BY MEMBERS OF THE RESEARCH TEAM

Albert Doolittle and Charles Rockwell. "Instrumenting the Arks." Submitted to Spectrum, Journal of the Institute of Electrical and Electronic Engineers.

John H. Todd. "Looking for a New Aquaculture: The Roads Ahead." Published in The Commercial Fish Farmer, July, 1978, 4(5): 37-29.

John H. Todd. "Economics, Ecology, Appropriate Technologies and Small-Scale Aquaculture: A Brief Personal Statement.", and "Windmills: An Appropriate Technology for Aquaculture." Published in The Commercial Fish Farmer, September, 1978, 4(6): 6-7 and 8-10. John Todd organized this issue of the magazine, basing it on the theme "Small-Scale Aquaculture and Appropriate Technologies".

John H. Todd. "Where Have All the Fishes Gone?" (Title and author missing from published article.) Published in The Commercial Fish Farmer, March, 1979, 5(3): 24-28.

John H. Todd. "Dreaming in My Own Back-Yard." Accepted for publication in The Commercial Fish Farmer.

John Wolfe, David Engstrom and Ron Zweig. "Sunlight Patterns Without, Chemistry Patterns Within: The View from a Solar-Algae Pond." Accepted for publication in The Journal of The New Alchemists, No. 6.

John Wolfe and Ron Zweig. "Summary of Fish Culture Techniques in Solar-Algae Ponds." Accepted for publication in The Journal of The New Alchemists, No. 6,

John Todd and John Wolfe. "Agriculture and Aquaculture in Bioshelters: The New Alchemy Experience." Published in The Bulletin of the New Mexico Solar Energy Association, March, 1979, 4(2): 7-10.

John Wolfe. "The Energetics of Solar-Algae Pond Aquaculture." Accepted for publication in The Journal of The New Alchemists, No. 6.

John Wolfe. "The Great Champagne Race." Published in The New Alchemy Newsletter, Fall-Winter, 1978.

Ron Zweig. "The Dome as Nursery." Accepted for publication in *The Journal of The New Alchemists*, No. *6*.

Ron Zweig. "Native North American Polyculture: A Beginning." Accepted for publication in *The Journal of The New Alchemists*, No. *6*.

Albert Doolittle, David Engstrom, John Todd, John Wolfe and Ronald Zweig. "Aquaculture and Its Place in Solar Architecture." Proceedings of "Solar Greenhouses: Living and Growing" Conference, April 6-8, 1979; Plymouth, MA.

Ron Zweig. "Solar Aquaculture: Historical Overview." Accepted for publication in *The Journal of The New Alchemists*, No. *6*. The article is not included here because of its previous submission to the National Science Foundation in the Interim Report, August 24, 1978.

129

INSTRUMENTING THE ARKS

by

Albert M. Doolittle, Jr.
New Alchemy Institute

Charles Rockwell
Microlog, Inc.,Guilford, Ct.

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INSTRUMENTING THE ARKS

Outside it is a bitter -10°C. A strong gusty wind is skimming snow from one drift to another, and has driven the wind chill factor down to nearly -40°C. Although the nearby building has no furnace, it is nearly 25°C inside. It is quiet here with only the gentle murmur of flowing water and the occasional splash of a playful fish. The light coming through the fiberglass roof is soft and diffuse, and there is a warm, earthy smell.

A man is working his way down a long line of head high tanks, filling small bottles with water samples. When he has finished he will carry the samples to a nearby farmhouse and run a complex battery of chemical tests, including a spectrophotometric analysis. Nearby, a woman is watering a plant bed with the aid of a computer printout of soil moisture profiles that was generated only a few minutes earlier.

The two people, one a part-time goldsmith and part-time chemist and the other a full time gardener, are conducting experiments for The New Alchemy Institute. This small non-profit research organization's major thrust is the exploration of various means by which the needs of humankind can be supplied by the renewable resources of the earth. Research projects range from small scale aquaculture and agriculture experiments to the development of solar and wind power systems.

The building is the Cape Cod Ark, one of two solar heated greenhouses and experimental stations that were designed and built by The New Alchemy Institute working with Solsearch International of Cambridge,Ma.

This Ark and a more complex one situated on Prince Edward Island, Canada are used by New Alchemy Institute to test the concept of low energy food production in cold climates. New Alchemy Institute has pioneered the integration of energy conserving solar architecture with biological systems in an attempt to encourage small scale agriculture. Large translucent water tanks function as both a heat storage for the Arks and as an environment for breeding and raising of fish. Waste water, rich in nutrients from the fish tanks, fertilizes conventional planting beds. Additionally, different types of solar heating and cooling systems, both active and passive, are installed to evaluate their performance.

Natural biological systems are extremely complex. There are a tremendous number of variables that must be closely monitored and/or controlled if experimental results are to have any validity. Initial research instrumentation at the Arks was comprised of an array of battery-powered meters and strip-chart recorders. The resulting measurements were recorded in notebooks and any data reduction was done by hand. Gathering the readings from the various instruments and assembling the resulting data into usable form proved to be both time consuming and error prone. Statistical analysis of the data was very difficult because the data had to be converted by hand into a form that could be read by a computer, and then transported to the nearest computer center for processing.

The need was apparent for a computer system that could continously monitor the many sensors that were installed in the Ark, record the data at frequent intervals, and maintain the data in files that would be available for later analysis. Such a system would also enable mathematical models to be tested against experimental data, providing an extremely powerful research tool. More importantly, this system would free valuable and talented people from the drudgery of reading and recording meter readings.

The technical constraints on the computer system were severe. The sheer mass of data to be collected and stored demanded that the system have some form of disc data storage. The data was being collected in an environment that can only be described as hostile to electronic components; temperatures could range from 10°C to 35°C, and the relative humidity was rarely below 80%. Computer systems normally occupy environments that have air-conditioning and filtering: the floor of the greenhouse is dirt.

With growth and changes in the research programs it was necessary to develop a system that was both flexible and easily reconfigured. Obviously, the system had to be reliable, and supply accurate measurements.

The non-technical constraints were even more severe. The system would be operated by people with no special training or interest in computer systems. The research program at The New Alchemy Institute involves persons of diverse educational backgrounds, interests, and fields of expertise. The interactions within the group are very valuable because of this diversity. The computer system could not become a tool of a priviledged few, but had to be integrated into the workings of the Institute at all levels. The system had to be approachable.

Finally, there were severe financial constraints. New Alchemy Institute's major funding is by private contributions and some support from federal agencies. The initial cost, system maintenance and upkeep had to be limited by the budget.

Ultimately, the problem of the selection of a computer system resolved itself into three broad requirements: a powerful minicomputer with disc storage for data analysis residing in the office area; a data acquisition system installed in the greenhouse; and the computer software necessary to link the data acquisition system to the minicomputer, process and present the data in usable form.

For the minicomputer system we chose the Digital Equipment Corporation PDP-11/03, with 28^K words of memory, a dual floppy disc system, and a VT-55 terminal with graphics and hard copy capability. Although it is relatively inexpensive, the PDP-11/03 has nearly all of the power of the more expensive PDP-11 family members and easily meets the need for data reduction and analysis.

The data acquisition system was supplied by Microlog, Inc., of Guilford, Ct. It is a modular microcomputer system primarily for data acquisition and control applications. A wide variety of plug-in modules were available that could interface directly with our many types of sensors. The flexibility easily met our needs for a data acquisition system.

In March 1977 the two systems were installed; the PDP-11 in the office area, and the Microlog system in an isolated chamber in the greenhouse. The two systems communicated over a 20 mA current loop. The Microlog system was programmed to wait for a command from the PDP-11. When a measurement was necessary the PDP-11 would transmit the request to the Microlog system and continue with its processing. The Microlog system would select and deselect the appropriate channel, make the measurement, and issue an interrupt to the PDP-11 system when valid data was available. The Microlog system has been recently been reconfigured as a stand-alone system programmed in BASIC. Data is collected and stored on micro tape cassettes, and read into the PDP-11 when convenient.

Software for the PDP 11/03 was written in RT-11 FORTRAN, a software system with many person-years of programs already available. The FORTRAN programs requested the appropriate measurements from the Microlog system, converted the data into a form that was meaningful, and displayed the resulting information, either in tabular or graphic form. The raw data was preserved on floppy disc for analysis of long term trends, and as a data base for mathematical modeling.

As the system is currently configured, it is monitoring 56 channels of analog input from various sensors and instruments with an additional 16 channels of control input and output. Data is obtained on outside air temperature, wind velocity, wind direction, dew point, and solar insolation (the power density from the sun in watts/square meter); inside air temperature and relative humidity; water tank temperature, dissolved oxygen, and pH; and soil temperature and soil moisture.

When it is necessary to make changes in the parameters being monitored, the experimenter simply rearranges connectors from the appropriate sensors on the Microlog panel. Data collection software is controlled by a PDP 11 disk file containing the configuration parameters. By editing the disk file using a simple menu option list the experimenters need not have extensive knowledge of high level languages.

The data acquired is used by each experimenter to aid in evaluating ongoing experiments. The part time chemist uses the data in conjunction with the chemical analysis of the water, algae density, and fish density and growth rate to study the problems of maintaining high population densities of fish in the tanks. The gardener is evaluating different varieties of vegetables the can be grown in the winter months. The chemist's analysis of the irrigation water is available in a computer data file and is used to determine the nutrient content of the water. The soil in the garden plots and the water in the fish tanks, both heated by the sun, act as thermal storage systems. The temperature data obtained by both the chemist and gardener is used by the building evaluation group in determining the heat capacity and solar heating efficiency of the building.

Through the sharing of monitoring tasks and data files each researcher is able to relate the data from a specific experiment to the data obtained by others. A better understanding is gained for individual experiments and their interactions with the overall environment of the Arks.

The computer system is also being used to partially control the environment of the Arks. Fish tank aerators are turned on if the dissolved oxygen in the water falls below safe levels for the fish. Door and roof vent closures are monitored, and roof vents are opened and closed to aid in maintaing a constant temperature in the building. Complex predicitive algorithms are being developed to control various parameters of the solar heating system in an attempt to improve its efficiency. Program control of the heating system enables various control sequences and algorithms to be tested without requiring costly changes in controller hardware. The existing hardware controllers remain for back-up and fail-safe supervision of the computer system.

The knowledge gained from the experiments and the data collected by the monitoring system are being used to develop mathmetical models to aid in the understanding of the complex interactions within the environment, and as a tool to optimize the performance of the Ark. A DYNAMO compiler has recently been installed on the PDP-11/03. DYNAMO, a sophisticated computer language that has been designed for computer modeling of complex systems, has only been available on large scale computer systems. This is the first successful installation of a PDP-11/03 computer. With DYNAMO, The New Alchemy Institute is able to develop models quickly and easily, without having to resort to outside time-sharing services.

Although the Arks are experimental structures, The New Alchemy Institute is using the data and experience gained from the Arks to bring Ark-type structures closer to the average homeowner. The Institute is designing a passively-heated house for a New England location. The house embodies a distillation and integration of ideas developed at The Alchemy Institute and elsewhere. By using energy-conserving design and construction techniques, it is expected that 90% of the heating requirements can be met with passive solar energy.

The project to instrument the Arks has been a gratifying success. A small system has been developed that has met the requirements without a crushing financial burden. The system is logging data reliably, is easily reprogrammed and reconfigured to meet changing needs, and is being used throughout the Institute. Comments from both users and observers have been extremely favorable.

The reason for this success is not due to any dramatic advance in the state of the art; it is because the analog hardware, digital hardware, and computer software have been integrated into a system that provides a solution to the problem of data acquisition while remaining nearly transparent to the user. The system proves exemplary in meeting New Alchemy's present research needs. Moreover, it has the potential to grow. Although this system was configured for a research environment, the experience gained could be applied to most monitoring and process control needs.'

The New Alchemists

To Restore the Lands, Protect the Seas, And Inform the Earth's Stewards

Looking for a new aquaculture:

The roads ahead

By John H. Todd

To say that my life changed that day would be an oversimplification.

For a long time, I had wanted to have a look at a renowned experimental fish culture installation — the brainchild of a distinguished scientist. If I told you I had been invited to visit, I am afraid I would be stretching the truth. My crony and I were much younger then, and we tended not to stand too much on formality — which is a windy way of saying we decided to sneak in.

One morning, as casually as possible, we sauntered in, poked around, sniffed the air a bit and inspected the model facility, which was touted in all the best papers as the aquaculture farm of the future. My friend (the one who co-authors this column, Bill McLarney) and I were filled with high expectation. We earnestly desired to assess the state of the art. And being neophytes to fish culture, this kind of visit seemed the only way to go about it.

As it was early in the morning and no one was about, we looked around as best we could. I was impressed. No, that's not accurate. I need stronger language. Maybe awed is the word. Bevies of pools, batteries of pumps, aerators, filters, back flushers, ozonators, infrared irradiators, filters, timers, feeders and miles of wiring and plumbing greeted our eyes. Then there were the sensors, probes, records and electronic gear that took our breath away. We were seeing space age aquaculture firsthand.

The whole rig looked like a NASA (National Aeronautics and Space Administration) space lab with the cowlings off. I can't tell you how excited I was. I was sure this demonstration of an engineering triumph should sustain undreamed of numbers of delectable creatures.

Stepping and stumbling over the paraphernalia, we inched up to the pools themselves. Whipping out our Polaroids, we prepared for the real show. Containing our anticipation, we peered into the swirling water.

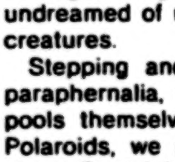
Fish finally appear

At first, I saw nothing. Then, as my Bausch and Lombs — and my eyes — began to acclimate, the life within revealed itself.

"Hey, Bill," I said, "there are fish in here."

I started to count the fish — using my usual one finger at a time method so the numbers wouldn't get away from me. The fish were swimming by slowly. By the time I had worked my way up to the fourth finger on my left hand, I had exhausted the population. Not believing my eyes, I waited until they came around again. This time, I managed to count my way to my thumb.

Editor's Note — John H. Todd, Ph.D., and Bill McLarney, Ph.D., head the New Alchemy Institute of Woods Hole, Massachusetts — an international research and educational organization. The two share the task of writing this column, which is a regular feature of the COMMERCIAL FISH FARMER.



"I guess you missed one the first time around — or squeezed two fingers on the second counting," snickered Bill.

"At this rate," he went on, "it looks as though there are more electronic pumps than fishes around here. It must be one of those utility-sponsored projects."

It would be an exaggeration to say that that is all we saw. If memory serves me correctly (and it is prone to lapses), there were, in one or two of the pools, a few milk-carton-sized racks filled with some clam species or other — perhaps a pioneering polyculture experiment was being launched.

Just a prototype

We repaired to a local saloon to calm down a bit. Later we learned from official sources that what we had seen was a prototype. It still had bugs in it. But bigger things were in the works, and solid government backing was believed to be just down the road. It seemed to our still innocent eyes that this type of techno-twit's vision might engineer aquaculture out of existence in this country. All that paraphernalia seemed a blatant denial of nature's skills.

I wondered if the ex-aero space

guys trying to manage us with their toys know that the living world has equivalents to their expensive machines — equivalents that are cheap, self-repairing, reliable and don't need fossil fuels. About the only thing the fancy hardware can do that nature can't is make millionaires out of manufacturers and engineers.

Don't get me wrong — please. I am no stone ager, advocating technology-free fish farms. There are times when we mortals need help. Besides, anybody who has seen the wind-engines, bioshelters and solar aquaculture courtyards at New Alchemy knows that we are into technology — but the kind that serves natural or living systems — and only as junior partners.

Since that day, I have done a lot of reflecting. I am coming to believe that many of my fellow aquatic scientists are working from an incorrect premise. Namely, they are trying through various ingenious means to make aquaculture environments match precisely the needs of a few commonly cultured fishes such as trout. I have listened with patience to their arguments for doing so which revolve around market potential, consumer tastes, and sales prices per pound. Their considerable skills are focused on vaccines, medicines, nutritional needs, and chemical and engineering components of culture systems. Yet the best efforts of research and development programs scarcely seem to alleviate the energy, capital, feed, water quality and disease problems which plague aquaculture.

What is the answer?

There is no single answer to anything that's valuable. There is a road that can be followed, and I want to explore it with you. After that fateful day, Bill and I began to think in terms of inverting the whole equation for aquaculture — using as guides modern ecology and the collected experience of oriental fish cultures.

Work in stages

We decided to begin by designing and assembling productive environments and stable ecosystems within which fishes could be grown easily and cheaply. That was Stage 1. During Stage 2 we set out to find the fishes to fit the designed environments. The whole globe became our beat.

This approach was not quixotic. In less than a decade, several of the species we have cultured in semi-closed warm water ecosystems have developed real market potential. The best known, tilapia or St. Peter's fish, sell in large cities, including New York and Chicago, at prices that would swell the heart of any fish farmer.

The long-range strength behind this ecological-design and fish-matching concept lies in the fact that there are so many fishes to choose from. Most of us really aren't aware of this. I would be willing to put money on fishes providing most of the new foods for our hungry world over the next hundred years. Fish are the last, real, untapped, human food resource. Despite having had a globe-wandering fish gourmet for a doctoral professor, it has taken me a long time to overcome my deeply ingrained prejudice that trout, salmon and catfish were the only species worth bothering with.

There are probably more fish species than all other vertebrates combined. If one takes all the birds, frogs, lizards, reptiles including snakes, turtles and lizards and adds to these all the mammals from mice to elephants, blue whales and people, the total number of species approaches 21,000. Estimates of modern fishes vary from 15,000 to 40,000 species. It may well be when and if they are all discovered and identified that their actual numbers will settle out at approximately 25,000 species. A goodly percentage of these reside in fresh or brackish waters.

Only a few cultured

We don't know much about them; only a small fraction have been cultured. Beyond this, very few have been evaluated as candidates for fish culture. I applaud the Fish Culture Section of the American Fisheries Society for their addressing this problem at Aquaculture/Atlanta/78.

Yet, with some temerity, I would suggest that aquaculture is hurting for lack of a wholistic, ecological perspective. Most polyculturists use a handful of species culled haphazardly from world stocks. We don't know that freshwater prawns, tilapia or Chinese carps are the way to go. Other species may have more to offer.

One of the great, untapped reservoirs for new human foods is South America. The Amazon and Orinoco River basins gave birth to over 2,000 species of freshwater fishes. Yet, this continent having the richest and most diverse fish fauna has scarcely been explored by aquaculturists. The range of fish types is enormous. One — an armored catfish — is a veritable mountain climber. It has a holdfast organ, which is part of its mouth, that it uses to scale mountain streams to an altitude of 15,000 feet. More endearing in a culinary sense are species of characin, South American catfish and cichlid families with a reputation of pure ambrosia when it comes to eating.

Machaca eats wastes

Nobody knows how many of these fishes might be cultured in ecologically derived environments. There are some clues to support my case. One species we have worked with in Costa Rica is a characin, *Brycon guatemalensis* — known to the local people as machaca. The diet of this fish would gladden any fish farmer — it consumes terrestrial detritus like leaves, wild fruits and nuts, almost anything that falls into their infertile stream homes. Their teeth would make a shredder-grinder executive green with envy. Machaca uses the biologically inherited machinery in its mouth as potential replacements for shredders, choppers, and spreaders down on the fish farm, while growing fat and tasty on what, in our society, are normally considered wastes.

I am not suggesting that the machaca is the only answer to our problems. We have all heard that story before. I do think though that unknown riches await a systematic search of the fishes of South and Central America.

My tale has a tragic shadow side. The search for fish species suitable for culture must begin soon because the New World tropics are being

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deforested. Streams are silting in as the surrounding forests are devasted. Many fishes are threatened. Extinction might be in store for some. How quickly the ecological destruction is proceeding can only be guessed. But, when one man — America's only multibillionaire, Daniel K. Ludwig — has cut down millions of acres of Amazon jungle, equivalent in area to the size of Connecticut, to grow a single species of tree for pulp and paper, you can bet that the fishes indigenous to this private fiefdom will suffer.

I seem to be announcing that there are untold new fishes available for culture and, at the same time, slamming the door — saying they might not still be there for much longer. If it were to become widely known that South American waters contained biological "gold," the ecological destruction of the forests might be slowed. Cynically, I suspect the possibility of wealth to be the basis of decision for many people. By proving that wealth lies not in exploitation but in the careful husbanding of aquatic environments and in the forests that surround them, then the fishes stand some hope of being saved and, in turn, might provide a foundation for New World aquaculture.

I should clarify what I mean by the use of these fish in aquaculture. I am not advocating that Amazon or Orinoco River fishes be stocked in North American lakes. The casual introduction of exotics can prove disastrous. I am recommending rather that large numbers of them be studied for their culture potential. The most promising could be cultured in their native areas, in tropical areas where native fishes are lacking, and in solar heated, semi-closed culture ecosystems in northern industrial countries, a la New Alchemy.

Having covered so much ground, I should like to retrace my steps briefly. I have said that aquaculture is headed down the same cost-spiralling road that threatens agriculture. The addiction to fuels, chemicals, increasing amounts of machinery and rising land taxes, etc., which cause production costs to skyrocket at a rate greater than the market value of foods at the farm gate, should cause us to reconsider our general direction. With this scenario the last person to make money is the fish farmer.

I am proposing that aquaculture diversify its options. This has been said in these pages before. I am merely urging that aquaculture shift towards a more complete biological model. It should shift the emphasis from engineering culture environments that precisely fit the needs of a few fish species with narrow and specific environmental and water quality requirements to the designing of environments that are ecologically balanced, stable and productive.

The name of the new game is the substitution, where possible, of ecological knowledge for capital, energy and hardware. The next step would involve the enlarging of the fish repertoire of the aquaculturist by finding species that match biologically designed environments. Finally, I would suggest that — in the task of building an aquaculture that can thrive in a time of economic and resource uncertainties — the fishes of the world have scarcely been tapped.

I would be very interested in hearing from readers who are evaluating various fish or who have leads on potential species for culture.

(John Todd's address is: The New Alchemy Institute East, P. O. Box 432, Woods Hole, Massachusetts 02543.)

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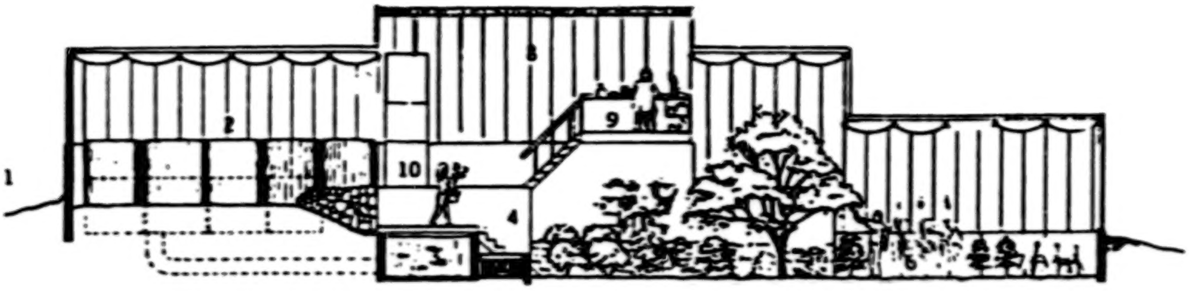

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Economics, ecology, appropriate technologies and small-scale aquaculture:

A brief personal statement

By John H. Todd

Recently I have been engaged in designing small fish farms intended to be viable economically. I have borrowed ideas and technologies developed at New Alchemy centers and from other organizations like Solar Aquafarms. My goal was to conceive ecologically inspired microfarms that made economic sense. I had in mind a farm for a couple or a family with access to a small piece of land and a minimal amount of water.

The designs were by no means scaled-down commercial fish farms specializing in large-scale production of a single species. Instead they were diverse, for enough shared functions lie in diversity to give small-scale fish farms their economic strength. They are further characterized by a high degree of integration; solar and wind technologies are tied to architectural concepts that, in turn, can link ecological pathways and networks to marketable entities such as fishes, agricultural crops and the propagation of young trees. All of these cycles are interconnected and would help reduce the cost of such microfarm's costs.

Editor's Note — John H. Todd, Ph.D., is an internationally prominent researcher, who — along with Bill McLarney, Ph.D., another leading aquaculture scientist — directs the New Alchemy Institute (P. O. Box 47, Woods Hole, Massachusetts 02543. Telephone: AC 617/563-2655). Todd and McLarney co-author the New Alchemist column, which is a regular feature in the COMMERCIAL FISH FARMER. New Alchemy's major emphasis is on the development of techniques for small-scale aquaculture.

Todd wrote this article as an introduction to the special issue on Small-Scale Aquaculture and Appropriate Technology. *He also is author of the second article in this section* Windmills: An appropriate technology for aquaculture.

I should like to give an example of how an appropriate technology can aid a small-scale aquaculture-based farm in diverse ways. For my example, I shall focus on the solar-algae ponds which Bill McLarney and I described briefly in the September '77 issue of the *Commercial Fish Farmer*. When solar-algae ponds, which are translucent fiberglass silos, are placed within a solar greenhouse they absorb radiant solar energy so effectively that they can pay for themselves on their heating ability alone. Their incorporation in greenhouses or bioshelters eliminates the need for fossil fuel heating at least here on Cape Cod. This is valuable as roughly half the cost of greenhouse flower and food production now is tied up in fuel costs.

The solar-algae ponds are not just heaters; they are superb fish-raising entities. Their sun-warmed waters support dense algae blooms and a rich profusion of life much of which is edible for fish. Pond conditions are close to optimal for a variety of valuable fish species. (See photo)

To the small-scale commercial designs I have added agricultural crops including vegetables and flower seedlings thereby completing another link. Wastes from the solar-algae ponds provide nutrients and warmed irrigation water for potentially high-priced off-season vegetables and flowers. In turn the agriculture contributes waste products including some weeds back to the aquaculture. The accompanying drawing shows the topographical relationships in the Cape Cod Ark, our present microfarm.

There are other ecological and economic linkages. Moist warm air within the solar structure lends itself to tree propagation. Mist-propagating technologies would facilitate the rooting of thousands of tree cuttings. Trees, especially fruits and nuts, are valuable and find ready markets in most urban areas.

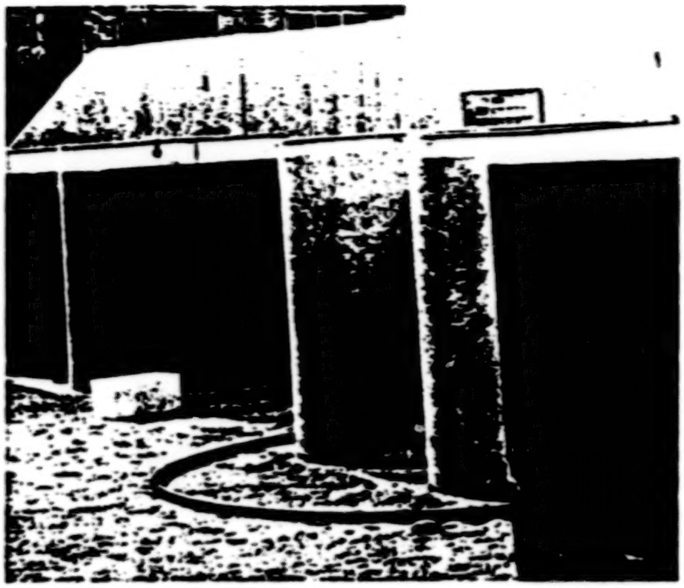
Even the aquaculture should be diversified. Young tilapia could be reared in solar-algae ponds and then fattened to one-pound size in shallow outdoor ponds in summer. Some of the crop could be held indoors through the fall and winter for sale as live fish to restaurants. In the New Alchemy Ark on Prince Edward Island, interconnected solar-algae ponds have been used for hatching and rearing trout in the winter. The trout are grown to size in floating cages and ponds in summer and fall.

Combinations abundant

The potential combinations of species and markets may be more limited by our imaginations than anything else. A friend once smugly told me he couldn't understand why I raised fish to sell for a dollar or two a pound as food. He allowed that the same skills often bagged him over $100 per pound for exotic aquarium species. His message is that the small fish farm shouldn't overlook the tropical aquarium market for it may well help pay the bills.

I would like to conclude by framing the small, diverse solar-based fish farm in the context of the present and the future. It has not yet dawned fully on us as a society that we are already in the early phases of a post-petroleum era. We still think and behave as we did in the 1950s. Oversized cars, foods transported from halfway round the world, centralized energy, and large multinational corporations may well become the hallmarks of the past.

New forms still tentative are coming into being. Small-scale, decentralized, technologically flexible yet sophisticated energy, food, architectural and manufacturing networks are starting to emerge. Ecology, which is rapidly becoming a major design science, is allying itself with economics. It is my modest proposal that aquaculture could be a significant part of this.



The solar algae pond in the courtyard at New Alchemy Institute of Woods Hole, Massachusetts.

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Windmills:
An appropriate technology for aquaculture

By John H. Todd

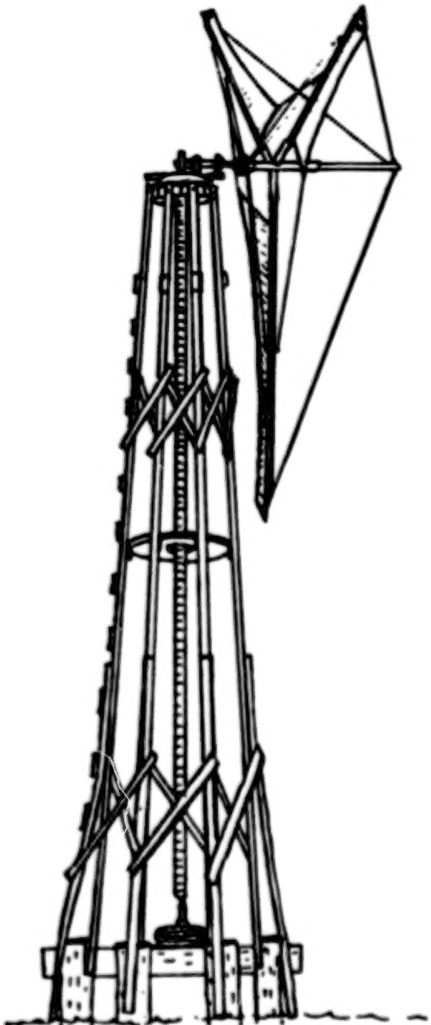
Most of the naturally productive waters of the world are found where there are periodic currents or continuous flows. Oceanic upwellings, biologically rich estuaries, lagoons, and tropical rivers support abundant life partly because their flowing waters facilitate rapid exchanges of nutrients, essential gases and organisms.

The same principles can apply in aquaculture. The most productive aquatic farms use rapid flows or strong currents as exemplified by the Galician Bays of the Atlantic coast of Spain. There, where mussels are cultured in powerful, plankton-rich currents, yields of 600,000 kg/h/year (approximately ½ million pounds per acre per year) are the norm. The Snake River Trout Company of Buhl, Idaho, is a relatively close rival to Spanish mussel farmers producing an equivalent poundage of trout (1970 production figures) on 10 acres. In the latter case the "secret" lies in the powerful springs which have a total flow of ¼ million liters per minute (approximately 60,000 gallons/min).

Perhaps the most telling demonstration of the importance of running water for productivity is that of common carp farming in Japan. In still water ponds, carp production runs about 5,000 kg/h/year with heavy fertilization and feeding. However, ponds with flowing water and streams yield 400,000 - 2,000,000 kg/h/yr (A kilogram per hectare is roughly equivalent to 2.2 pounds per acre) using comparable management techniques. Moving water nets over a 100-fold increase in production on a given culture area.

It does not seem far-fetched to consider that wind power be used in a variety of aquacultural enterprises where winds are available to simulate tidal currents and stream flows. In some cases this is done currently with electrical, gas, or diesel-powered pumps. Wind engines would have the advantage of freeing us from further depleting our dwindling petroleum reserves and from skyrocketing electricity costs.

Windmills can serve other functions for fish farming. They can be used to circulate water through semiclosed rearing facilities, or pump up water from a well or lake into raceways and rearing ponds. The wind-powered pumping device is particularly in its element wherever sporadic water changes or flows are needed.



Windmills can power air compressors which aerate and turn over the water in ponds thereby minimizing low oxygen and stratification conditions. There is presently on the market a simple, wind-powered water stirrer which ranchers use to prevent stock ponds from freezing.* The same techniques can be used to prevent winter fish kills.

As the benefits of fish pond water and fish excretory products on agricultural crops become more widely realized, it is our contention that windmills will be used to irrigate and fertilize crops, including market gardens, using water from aquaculture ponds and raceways.

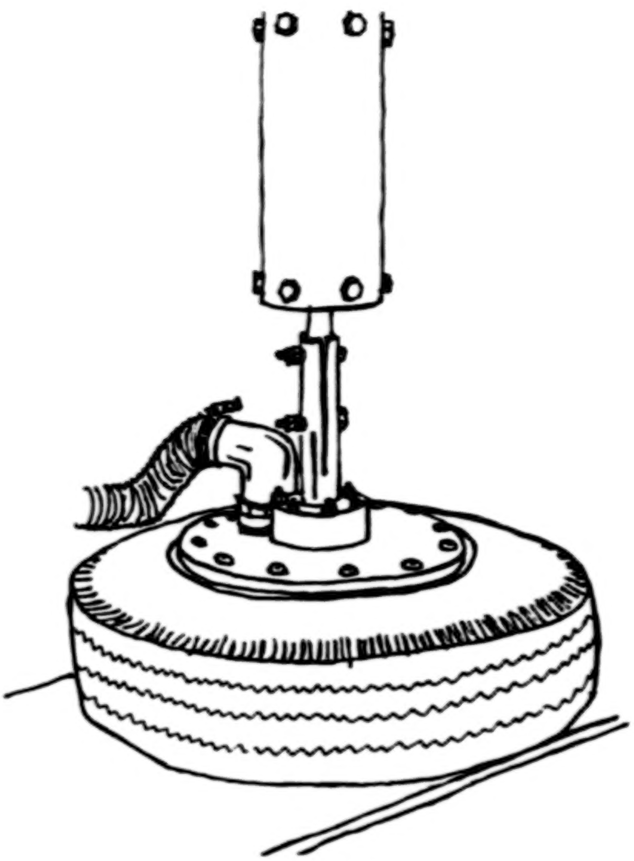
Windmills can have a wide range of end uses. A wind-powered refrigeration/freezing plant is presently being developed at New Alchemy. The by-product of the wind plant, namely heat and air under pressure, in turn will be useful in aquaculture. It seems hopeful that windmill/freezers may be a technology appropriate to many remote and/or tropical areas where there is no electricity, and rapid spoilage is a serious obstacle to fisheries development.

Wind furnace used

Windmills can play a role at the other end of the thermal spectrum when water is heated by wind-powered furnaces. We have designed a wind furnace which employs many of the same principles as our water-pumping designs. In the future, wind furnaces will be used to raise and control water temperatures on fish farms located in cooler regions.

At New Alchemy, simple windmills have been used to support a variety of experimental aquaculture systems. The first of these mills was a sailwing inspired by the ancient irrigation windmills on Crete which are still in use today. Our sailwing pumped water up from a lake some 20 feet below into a series of running water ponds where chironomid insect larvae were cultured as supplemental feeds for fishes. The periodic water changes provided by the wind machine were all that were needed to make the culture facility work well.

Our next windmill was a small S-rotor vertical axis machine. Its shaft was connected to an air compressor, salvaged from a paint sprayer. In winds above 5-6



The pump operated by "Bed Red"

mph, it pumped compressed air into a small aquaculture pond in a solar greenhouse several hundred feet away. The air was used for water circulation as well as aeration.

Our most beautiful windmill is a sailwing that is used for pumping water through a solar-heated fish-rearing complex. Fondly knows as "Big Red" (see cover photograph),* it circulates water at a maximum rate of 5,000 liters/hour (approximately 1,200 gallons/hr) through a recycling facility composed of two raceways and a pond. Each component is at a different elevation and connected via a channel to one below.

The windmill pumps water up from the solar-heated, plankton-rich lower pond and discharges it into the upper raceway. The raceways house growing populations of fish. The lower pond is fed by gravity from the raceways. The pond contains no fish but functions to purify the water and provide the basis for supplemental food chains that feed the fish in the raceways above.

The pump (see illustration) was designed to match the power output of the 20-foot diameter (6 meters) sailwing. It performs in relatively light winds yet retains the ability to pump in all but the strongest gusts. A small ¼ hp electric pump provides a residual flow through the system when the wind is not blowing. Tilapia, bullheads (*Ictalurus spp)*, Sacramento River Blackfish (*Orthodon microlepidotus*), common or mirror carp (*Cyprinus carpio*) as well as Louisiana red crayfish (*Procambarus clarkii*) have been reared successfully in the small wind-powered facility.

Technology still primitive

The biggest drawback to the employment of windmills in aquaculture is the state of the technology which, to be blunt, is as yet relatively primitive. One can purchase off the shelf water stirrers and the American multiblade windmills which

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still dot many of the farm lands of this country. But both types are inefficient and lack the power or output to justify their cost except perhaps in rare instances.

To date, windmill research and development has overlooked the needs of the aquaculturist. Research support is usually for large, showy electricity generating windmills. New Alchemy and other organizations that are trying to develop windmills relevant to aquaculture's needs find it almost impossible to obtain support for non-electricity generating systems. Be that as it may, I still think that wind engines will eventually play a significant role in many parts of the world.

A companion article of New Alchemy by Joe Seale (which follows this article) describes how such wind engines might evolve. The Seals article, while somewhat technical, points to the future of this very appropriate technology.

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**The design of "Big Red" will appear in the Fifth JOURNAL OF THE NEW ALCHEMISTS — available late fall/78 at $7.00.*

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The New Alchemy Institute at Woods Hole, Massachusetts, is an international organization that is dedicated to research and education "on behalf of humanity and the planet . . . and seeks solutions that can be adopted by individuals or small groups who are trying to create a greener, kinder world," according to its literature.

The institute's major task is the development of ecologically derived forms of energy, agriculture, aquaculture, housing and landscapes that will encourage repopulation and revitalization of the countryside.

The non-profit, tax-exempt institute derives its support from private contributions and research grants. Because it is concerned with ecological and social tools directed at small groups or individuals, it is not eligible for numerous regular channels of support.

New Alchemy has several membership categories. A Subscription Membership is available for $10 per annum to persons who desire to be included on the mailing list for newsletters and the institute's *Journal of the New Alchemists.*

An Associate Membership — a major source of support — is available for individuals and families at a cost of $25 per annum. It also serves as a subscription rate for businesses, libraries, universities and other institutions. Associates also receive the current annual *Journal of the New Alchemists,* newsletters and other special interest mailings detailing research progress reports.

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All membership contributions should be made payable to: The New Alchemy Institute, P. O. Box 47, Woods Hole, Massachusetts 02543. (Persons in foreign countries who desire to become Associate Members are encouraged to send international money orders or bank drafts in preference to checks drawn on foreign banks.)

A bibliography of New Alchemy publications is available on request.

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Last winter a sign was posted on the door of a local Cape Cod fish market. It said: "Temporarily closed due to high prices and lack of fish." The store is supplied by local fishermen and is independent of distant supply networks. Being close to the source, and near one of the country's greatest fishing grounds, it should have been less vulnerable than most fish markets.

Several months later the price of young, live eels mysteriously and rather ominously shot up to $1,000 a pound. Young eels were being flown to Japan where aquaculturists raise them to edible size. They were being transported half-way around the world to a seemingly insatiable market. Ironically several months later, the price dropped when the Japanese concluded that North American eels didn't taste as well as their own. However with eels in short supply, I am betting that they will come to appreciate the taste of the Atlantic eels. I was told that the atmosphere associated with the fishery on this coast was sinister and not unlike the drug trade where the stakes are high. Valuable and rare commodities, including eels, attract the underworld.

Cape Cod is named in honor of a fish which has been a traditional mainstay of New England's economy. The cod is under pressure too; recently an inshore dragger captain with a substantial vessel was quoted in the local press. He complained one bitter January morning: "Four passes, four damn passes in the snow. And what did I get for it? Not four-hundred fish . . . not forty. But four lousy fish, and small too, not even enough for supper." I had thought that his problem was that he specialized in such a sought-after species, but I was probably wrong. I have a friend, Bryce Butler, who is writing a book on a subject dear to his heart and nearer to his stomach, entitled *The Trash Fish Cookbook* which he is co-authoring with Bill McLarney who shares this column. The first installment of their book has already appeared in *The Book of the New Alchemists* (E.P. Dutton Press, New York). Lately, Bryce has been looking up fish brokers and various markets inquiring about trash fish. Old timers here would have one believe that half the ocean fishes caught in our waters are inedible and fit to be thrown back into the sea. There is a snobbery tied to what one eats and does not eat, or so the local myth goes. It was the little used and unappreciated fish that were the objects of my friend's quest; but he was told, in no uncertain terms, by fish buyers that there are no trash fish anymore. The term is obsolete. All fish command high prices. The wolf fishes, a big strange-looking blenny, is being used in the fish and chips trade, and I understand that they are good indeed. Even one of the most grotesque looking fish in God's creation, the goosefish, has become a fish of commerce these days. My friend was much saddened by this news. It's harder to write about trash fish cooking if there are no trash fish.

For some reason I don't fully understand, old notions die hard. It usually takes years, or even decades, for a new reality to catch up with events. There is a boom in fishing boat building these days that has been fueled by the optimism created by the two-hundred mile fishing limit. Every issue of my favorite newspaper, *The National Fisherman*, has page after page describing bigger and faster ocean-going vessels being built in places like Coos Bay, Oregon, New Bedford, Massachusetts, and Mobile, Alabama. These boats are getting more expensive—costing up to seven to eight million dollars—and they are getting more efficient at gathering up what remains in the sea. The hunt is on. The only force that might keep the oceanic hounds at bay, and save the fish stocks, is the rising cost of fuel. Fishermen with financial investments as large as these are going to find ways around any regulations that might be set up to curtail their activities. Their only alternative to bankruptcy may well be evasion of the law. Further, the crisis, and I don't think this is too strong a word for what I am describing, is not just confined to North America. It is worldwide.

Just over a year ago, travelling in southern Europe, the danger signs were unmistakable. In

Editor's Note — John H. Todd, Ph.D., is an internationally prominent researcher, who — along with Bill McLarney, Ph.D., another leading aquaculture scientist — directs the New Alchemy Institute (P.O. Box 47, Woods Hole, Massachusetts 02543. Telephone: AC 617/563-2655). Todd and McLarney coauthor the New Alchemist column, which is a regular feature in the COMMERCIAL FISH FARMER. *New Alchemy's major emphasis is on the development of techniques for small-scale aquaculture.*

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southern France ocean fish were in very short supply and their prices in market towns like Aix-en-Provence were far higher than beef, lamb or pork. The only reasonably priced fish served in restaurants were trout, which incidentally were superbly cooked.

In Italy, particularly in Rome, the situation was even more grave. One particular evening we were positively lusting after Italian fish cooking, and as good luck would have it we spied a small restaurant in a narrow, out-of-the-way alley which served fish exclusively. The smells emanating from the place were incredible. Waiting in line to be seated I watched a couple eating a modest looking fish followed by salad and wine and coffee for desert. As they paid their bill I peered over their shoulders to find out how much it was. I was stunned. Their meal cost them the equivalent of $75. With profound culinary regrets, Nancy, my wife, and I fled to take refuge in pasta elsewhere.

These figures are not intended as absolutely accurate or up to date. They are rough estimates based on prices that we have paid in the past and the weights of fish received.

The fisheries of the Greek Islands are severely reduced. The inshore waters seem picked over biologically. Wading in tidepools I found little in the way of animal life beyond the odd sea urchin and the rare, small fish darting about amongst the rocks. Considering the size of the vessels and the manpower in the fishing fleet, the return on their investment must be slight. One captain we befriended financed his vessel through taking tourists to out-of-the-way places for respectable prices. His livelihood as a fisherman had become almost a ritualized hobby and the odd fish that he caught were a cause for celebration.

My wanderings have turned up very little good news. Even the tropics of the new world are heavily fished. Near the New Alchemy farm on the Atlantic coast of Costa Rica on good days the best reef fishermen catch only a few pounds of saleable fish, and the coveted lobster are in short supply. Although Venezuela would apper to be a particularly favored country with a long coastline and major rivers, including the Orinoco, that transect it, a former student of mine, Stewart Jacobson, now studying the African killer bees there, wrote recently that it was difficult for him to learn much about edible species of fishes because there were so few around to learn about. He did say that red snapper in the local markets cost considerably more than filet mignon in the most expensive supermarkets. The famed bagre, or river catfish, didn't appear in his city's fish markets. And so the story goes.

It would seem logical to conclude that world fish shortages would have catalyzed aquaculture into action to fill the yawning gaps left by the depletion of wild stocks. I don't think that aqua-

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culture has yet responded to the challenge or to the need. And, with only a few notable exceptions, there may well be a comparable shortage of cultured species. I am basing this statement on the price and availability of young fish to fish farmers.

Several of my cohorts at New Alchemy and I have been making back-of-the-envelope calculations of fish stock prices and in most instances we have found that young fish are scarce and costly. The absence of hatcheries and fish stock may be a real bottleneck in the development of aquaculture. Perhaps the easiest fish to breed and hybridize is the tilapia for they can be spawned in large aquaria. Yet, at the present, some breeders are getting as much as $200 per pound for young hybrids. Incidentally, all my calculations are based upon batch lots of one-thousand fish. Non-hybrid tilapia can be bought for as low a price as $12 per pound. Some of the hybrid sunfish cost half as much as hybrid tilapia or approximately $100 per pound. The white amur, or grass carp, seem to be a better bargain. Their breeding requires hormones and some real experience. The young are shipped at a larger size and they can be purchased for between $22 and $50 per pound. As far as we can tell the best bargain in young fish is channel catfish which reflect the volume and the fairly sophisticated level of catfish culture. Young channel cats cost $4-$5 per pound. In some parts of the country trout may be comparably priced.

These figures with their wide range of from $4-$200 per pound for young fish, tell us that price and volume of cultured species are inversely related. This is certainly not news, but more easily bred fishes like tilapia should narrow the gap, which is not now the case. What is relevant and disturbing is the fact that many culturable species are in short supply. Hence the high prices and the scarcities. I am not faulting the fish breeders as they are not to blame. The underlying causes are in the structure of present day aquaculture.

My purpose in all this is to alert the aquaculture community to the possibility of a worldwide, as well as a national, shortage of fish. These shortages extend into aquaculture. In the past "trash" fish have been elevated to fill the gaps created by depleted fisheries and have saved the day for fishermen. These replacement fish, whether wolf fish or goosefish, are now legitimate leaving precious few unexploited fisheries. Now the onus is on aquaculture and it will have to see itself in a new light. A whole new generation of fish breeders, suppliers and growers are going to be needed and on a magnitude that we can hardly imagine. I have one suggestion. As a starter I propose that several of the lesser-known cultured fishes that feed low on food chains be farmed to replace ocean fishes in the large fish and chips market.

It would be a major task, but one well worth attempting.☐

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DREAMING IN MY OWN BACKYARD

by

John Todd

I have just finished my income tax forms and I realize with shaking hands and tears in my eyes, that I owe money to the Internal Revenue Service. It's becoming increasingly hard to ignore that living costs are going up faster than my income.

Gloomily, I retreat to the pond in my backyard to forget the tax man and to find my bearings. Thank God that it's the first warm day of spring and, as I settle down, I discover the muscovy and mallard ducks and the zany goats are happy to share this spot with me. I have, mind you, brought along a little extra corn to bribe my way into their company. We are soon joined by my nine year old daughter who senses my worries.

As the sun and these friends help me to forget, the place begins to come alive with the sounds and the smells of spring. I survey the scene. I live in a little, vest-pocket valley treed mainly with oak, locust and cherry. By local standards, some of these trees are very large. On the north-facing slope, next to the road, seven years ago I planted a small orchard of twenty varieties of apples, peaches and plums. The house, a typical small Cape Codder, sits on a terrace just below the orchard.

Behind the house, the land drops off, steeply in places, into a basin, then ascends again to my neighbor's house. The south-facing slope is a real sun catcher. The bottom of the basin is filled with a half-acre pond that extends into the yard of my other neighbor to the east. In the middle of the pond I have built a shack on stilts that is reached by a rickety bridge. I like working being surrounded by water and in the shack. It feels right. Although I am not sure why it helps to center me.

I am lucky to live in the woods, close enough to the sea to hear the fog horn and the storm-tossed surf. But still I am nagged by the bills and the tax man. To complicate matters, I plan to build a solar addition to the house that includes a greenhouse and tropical fish tanks. The fish tanks are intended to serve double duty by acting as solar heat storage units as well. It's an exciting project, dimmed only by the fact that it will more than double my mortgage.

Sitting on a grassy patch next to the pond, I enjoy the warmth and the stillness that is broken only by bird song. Although I can't feel it, the wind blows stiffly overhead and the gulls ride its wave at tree top height. Then my daughter and I get up to follow the goats over to an old abandoned stone well. As I stare into the well an idea begins to form. I see the land anew - there the ponds, the slopes, the house above, and the ducks including the wild ones that are attracted to this haven. I recollect that a couple of years ago my son grew a mess of bullheads to eating size in a single season in the shallow fertile pond. My mind is drawn back again and again to the well. The water level this spring is a foot from the top. The well is a key.

My head is filled with two streams of thought, there is the worry over money on the one hand and on the other the dream of wedding the sun, wind, the well, ponds, aquatic plants, fishes and ducks to create a mini-farm in this backyard. What if I were to think this through carefully enough? My little water farm might ease the financial burden by helping to pay for the new mortgage and for some of the household running costs. Might this be a sound way towards a greater degree of financial independence?

Within seconds I am pacing the property, banging on the pocket calculator, clicking my heels and designing a backyard water farm. My blood begins to boil as the sketches and plans start to unfold. [Figure #1]

In the first place, the existing pond is too small to do the job alone. As it stands now it wouldn't produce more than a few hundred pounds of fish a year. However, at the western end there is an old, elevated wagon road, and beyond it, between the road and the well, there is room for a second deeper 1/10th acre pond. But to be really productive I want flowing water too. Because the wind funnels down our valley, I imagine an American multiblade windmill that pumps well water into the ponds when the wind is blowing. Such a windmill could well increase the productivity of the water farm by an order of magnitude, or so I hope.

Although I have yet to work out all the design details it would seem wisest to pump the well water up into a series of solar silo ponds (yet to be described) then down into the new pond. The course of the water would be from the well through a series of solar silos into the first pond, then via a duct into the second existing pond. The water would be recycled by overflowing from the second pond back into the first. The exchange between the two would be dynamic and depending on the wind and their respective water levels. In my mind I have created a symbiotic, wind-powered water loop between the new 1/10th acre pond and the shallow, half-acre existing pond.

My plan then is to pump the water into a series of interconnected translucent fiberglass silos that are five feet high by five feet in diameter. Five or six of them would be adequate to absorb solar heat and to oxygenate the well water by photosynthesis before it enters the new pond. Running the water through a zig-zag course of black pipe would be a cheaper way of heating the water but would neither oxygenate it nor provide auxiliary feeds. Also it lacks any storage capacity that might come in handy during low oxygen conditions. With this scheme I am looking closely at the cost benefit value of a solar "river" composed of a series of silos as a way of optimizing the over-all system.

My plan would include an emergency ¼ to ½ horsepower electric or fuel-fired pump for periods when it is hot and windless and oxygen drops to dangerous levels. It would be there for insurance and I would hope that I don't have to use it. Electric aerators are not a good answer. Increasing their use would buttress the arguments of the utility boys who are promoting nuclear power plants.

The ponds are designed to be diverse ecosystems and to provide a goodly amount of the dietary needs of the fish. Nutrients would enter the ponds from several sources. Our household grey water would be piped through three solar silo ponds that would be filled with water hyacinth, aquatic ferns, duckweeds and algae. This way we wouldn't pollute the groundwater, as we presently do. The water-purifying, aquatic plants would, in turn, be fed to the ducks and fish.

Another major nutrient source would be the ducks. Right now I have only half a dozen, but in my mortgage-paying ecosystem, I would plan on 250 or so in a 680 square yard fenced impoundment connected to the half-acre pond. Their manure would fertilize the daylights out of the pond. The remaining major nutrient input would be the supplemental feeds fed to the fish and the ducks. Up to 12,500 pounds of fish feeds might be added to the system each year. A substantial percentage of it would enter the various food chains within the pond.

Fish culture would be seasonal and vary between the larger, shallow pond and the deep, new pond. The warm season crop in the shallow pond would include yellow bullheads, _Ictalurus natalis_, which are relatively fast-growing omnivores, blue tilapia, _Sarotherodon aureus_, a plankton and plant feeder and quite possibly mirror carp, _Cyprinius carpio_ var.

specularus, a benthic or bottom feeder. All three like warmish water and can withstand short periods of low oxygen. Ten thousand fish grown over a six-month period starting in April might well, with fairly heavily supplemental feeding and frequent water exchange, reach a marketable weight of 3,000-5,000 pounds. It is a guess, but I don't think an unrealistic one.

Between October to April another 500 to 1,000 pounds of fish like rainbow trout might be grown with the addition of sun-warmed well water, although this figure is pure speculation as I have never raised trout in quite this way before.

The small pond would be deeper, perhaps five feet in all. Though it is connected to the shallow pond, it might be less enriched with nutrients because it would receive the well water first. It would be here that I would plan to cultivate channel catfish, *Ictalurus punctatus*, and if I could get them cheaply enough, white catfish, *Ictalurus catus*. I would also like to try the fast-growing exotic characin, *Collosoma* sp., a fish that eats, and tastes like, fruit. If the small pond remained warm for long enough, I might get 1,000-2,000 pounds or more of marketable flesh from this pond. In the winter, trout should do well and perhaps add another 500 pounds to the total.

Marketing would be retail. Most of the customers will come looking for the crop. Some of the harvested fish would be kept in solar silos for live sale, perhaps to local restaurants among others. Some of the fish would be sold fresh once a week through the local health food store. The remainder I would cold smoke in a new smoke house that has been built recently by friends. Smoked tilapia and bullheads are mouth-watering, and sell for prices that really fatten the pocketbook.

As part of the whole design process, I have diagramed the energy, material and money flows through the water farm (Figure 2). Then on the back of the nearest envelope - the one containing my utility bill - I tabulated some of the economics (Table 1).

A first pass over the envelope suggests that there definitely is something to my backyard plan and that I should consider making the dream a reality. With some care and attention I might obtain between 5,000 and 8,500 pounds of marketable fish a year. Since the crop is small and the local market hungry for both smoked and live fish, it should be possible to gross between $8,500 and $15,000. The smoked fish sells at a minimum of $2.00 a pound. The remainder, I think, I could retail at an average of $1.50 per pound. Tilapia, which are low on the food chain, when sold as St. Peter's fish, should command even higher prices with organic food buffs. With a little advance notice before harvesting, I should be able to sell the crop with a minimum of effort and transport costs.

For an initial capital investment of $3,950 - $5,800 (keep in mind my backyard already exists) and an annual operating cost of between $1,600 and $2,450, I could realize a net annual return of between $4,950

DOUBLE SPIRAL DIAGRAM OF BACKYARD WATERFARM INTERRELATIONSHIPS

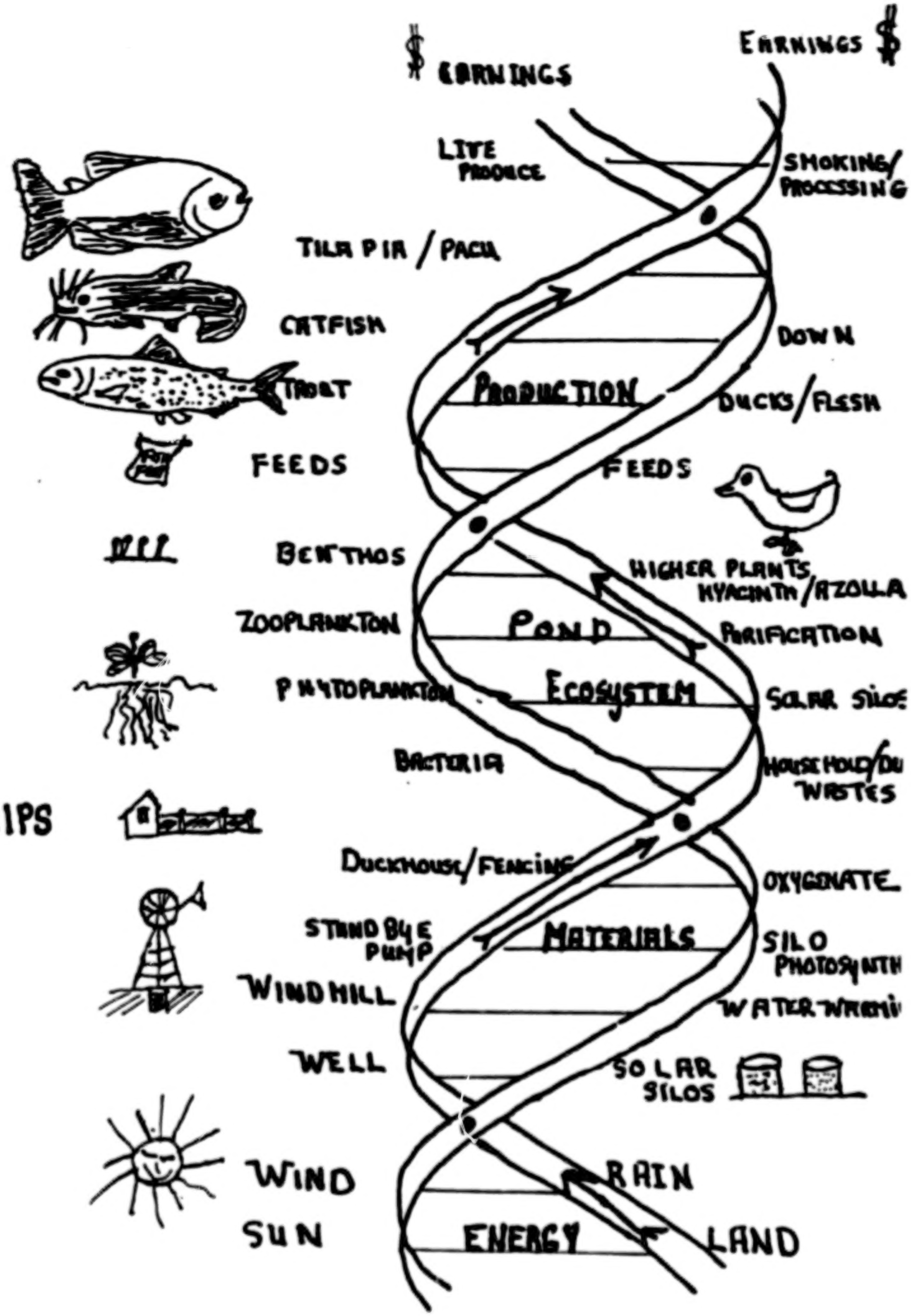

Figure 2.

TABLE 1. BACK-OF-THE-ENVELOPE ECONOMIC CALCULATIONS - BACKYARD WATER FARM

COSTS	AMOUNTS
Initial Fixed Costs:	
1. Backhoe	$ 500 - $ 500
2. Chicken Fencing	$ 600 - $ 600
3. Windmill plus Tower	$2,000 - $3,000
4. Solar Silos	$ 800 - $1,600
5. Emergency Pump - Used	$ 50 - $ 100
6. Duck House (Scrounged Materials)	-- - --
	$3,950 - $5,800
Annual Costs:	
1. Labor	-- - --
2. Fuel or Electricity for Pump	$ 25 - $ 50
3. Feeds	
A: 5,000-8,000 lbs catfish/ trout feed	$1,250 - $2,000
B: 2,500-3,000 lbs rabbit feed for tilapia/carp	$ 250 - $ 300
C. 1,000-1,500 lbs of marine fish waste	$ 100 - $ 150
4. Young Fish and Ducks (Bullheads Locally Trapped and Tilapia Locally Produced)	$ 500 - $1,000
	$2,125 - $3,500
Fixed Costs Amortized Over Six Years	$ 666 - $ 800
TOTAL ANNUAL COST	$2,791 - $4,300

PRODUCTION AND INCOME

Marketable Output:

Pond 1 - 3,000-5,000 lbs
(three species)
500-1,000 lbs trout

Pond 2 - 1,000-2,000 lbs catfish
500 lbs trout

Total .... 5,000-8,500 lbs

Plus 250 Ducks for Thanksgiving Market

Income:

2,000-4,500 lbs cold-smoked @ $2.00/lb	$4,000-$ 9,000
3,000-4,000 lbs live/fresh $1.50/lb	$4,500-$ 6,000
250 Ducks @ $3.00 apiece	$ 750-$ 750
	$9,250-$15,750
NET RETURN PER YEAR	$4,950-$12,959

and $12,959, if the fixed costs were amortized over six years. Since this is a family enterprise and friends would help with the harvest, I wouldn't have labor costs. In short, the water farm would more than pay for itself in its first year.

I know that at present I am still dreaming, but what with the price of fish climbing off the scales, and so many people looking for decent quality, poison-free, lovingly-grown foods these days, I think my fantasy is worthwhile. My daughter agrees.

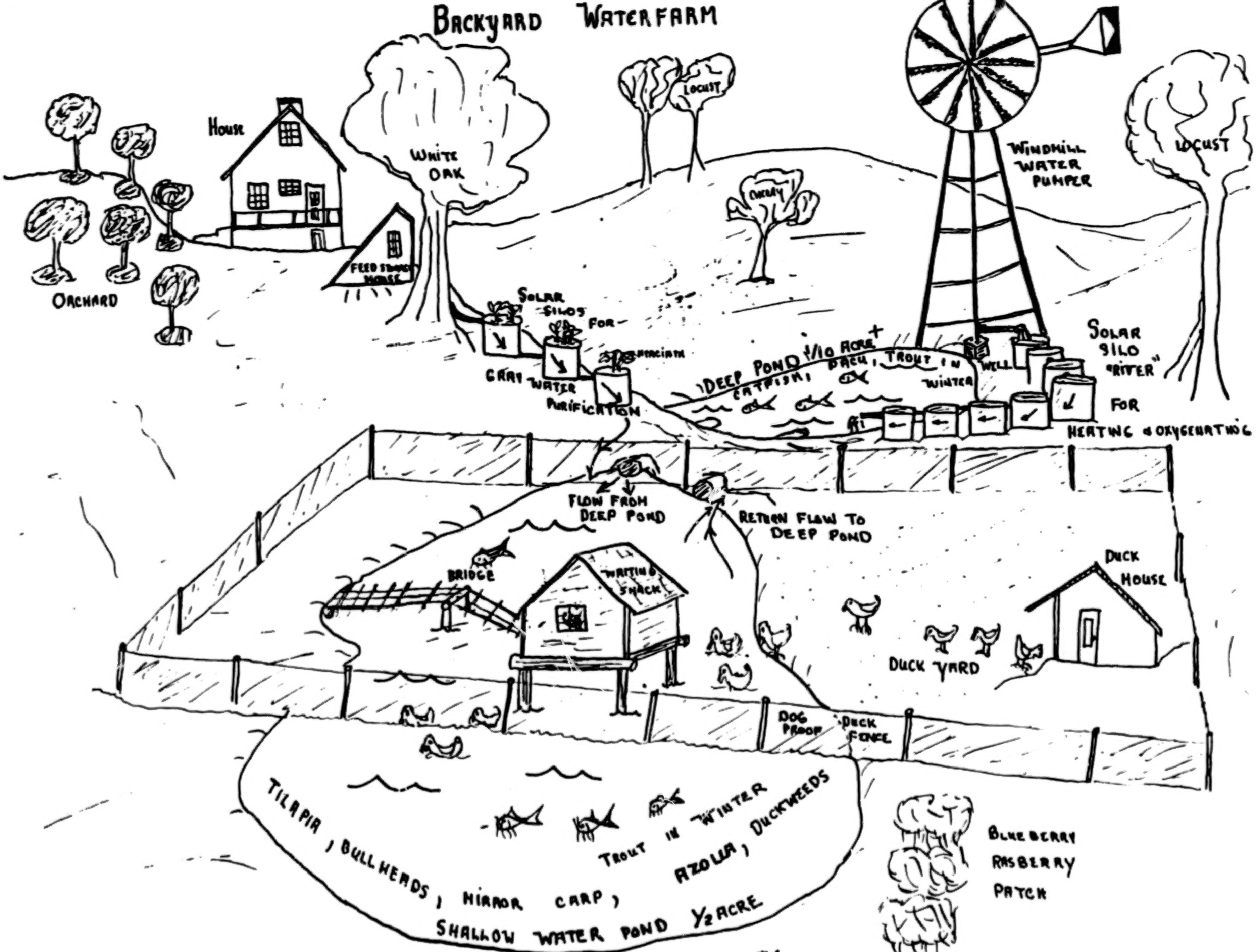
BACKYARD WATERFARM
House
ORCHARD
FEED STORAGE HOUSE
WHITE OAK
LOCUST
CHERRY
WINDMILL WATER PUMPER
LOCUST
SOLAR SILOS FOR GRAY WATER PURIFICATION
HYACINTH
DEEP POND 1/10 ACRE+ CATFISH, BASS, TROUT IN WINTER
WELL
SOLAR SILO "RITER" FOR HEATING & OXYGENATING
FLOW FROM DEEP POND
RETURN FLOW TO DEEP POND
BRIDGE
WRITING SHACK
DUCK HOUSE
DUCK YARD
DOG PROOF DUCK FENCE
TILAPIA, BULLHEADS, MIRROR CARP, TROUT IN WINTER, AZOLLA, DUCKWEEDS
SHALLOW WATER POND 1/2 ACRE
BLUEBERRY RASBERRY PATCH

FIGURE #1

feeds, comfrey being a prime example. Within each aquaculture tank the vigorous algae populations serve four functions: 1) darken the water column so it can absorb all incoming solar energy, 2) provide a part of the fishes' diet, 3) oxygenate the water, and 4) purify the water by metabolizing toxic fish wastes, including phosphate, nitrate, and ammonia. In the humus-rich soils and adjacent compost bin, bacteria and funguses generate heat and carbon dioxide (CO_2 depletion is a prevailing problem in greenhouses) while recycling organic wastes into plant fertilizer. With such multiplicity of function in nearly every component, high total system efficiencies result.

Energetics

The solar-algae ponds pay for themselves on their contribution to the climate of the structure alone. An input to output analysis yields a five-to-one positive energy contribution from the water storage system over its twenty year lifetime. The calculations are as follows:

INDIVIDUAL POND

INPUT

Cost of Fiberglass Container[4],[5]

$75 1.93×10^5 Btu/$
252 cal/Btu   1/20 yr =

182×10^6 cal/yr

OUTPUT

Heat Stored and Released[6]

2.5°C/day 2.4×10^6 cm^3
150 heating days/year =

900×10^6 cal/yr

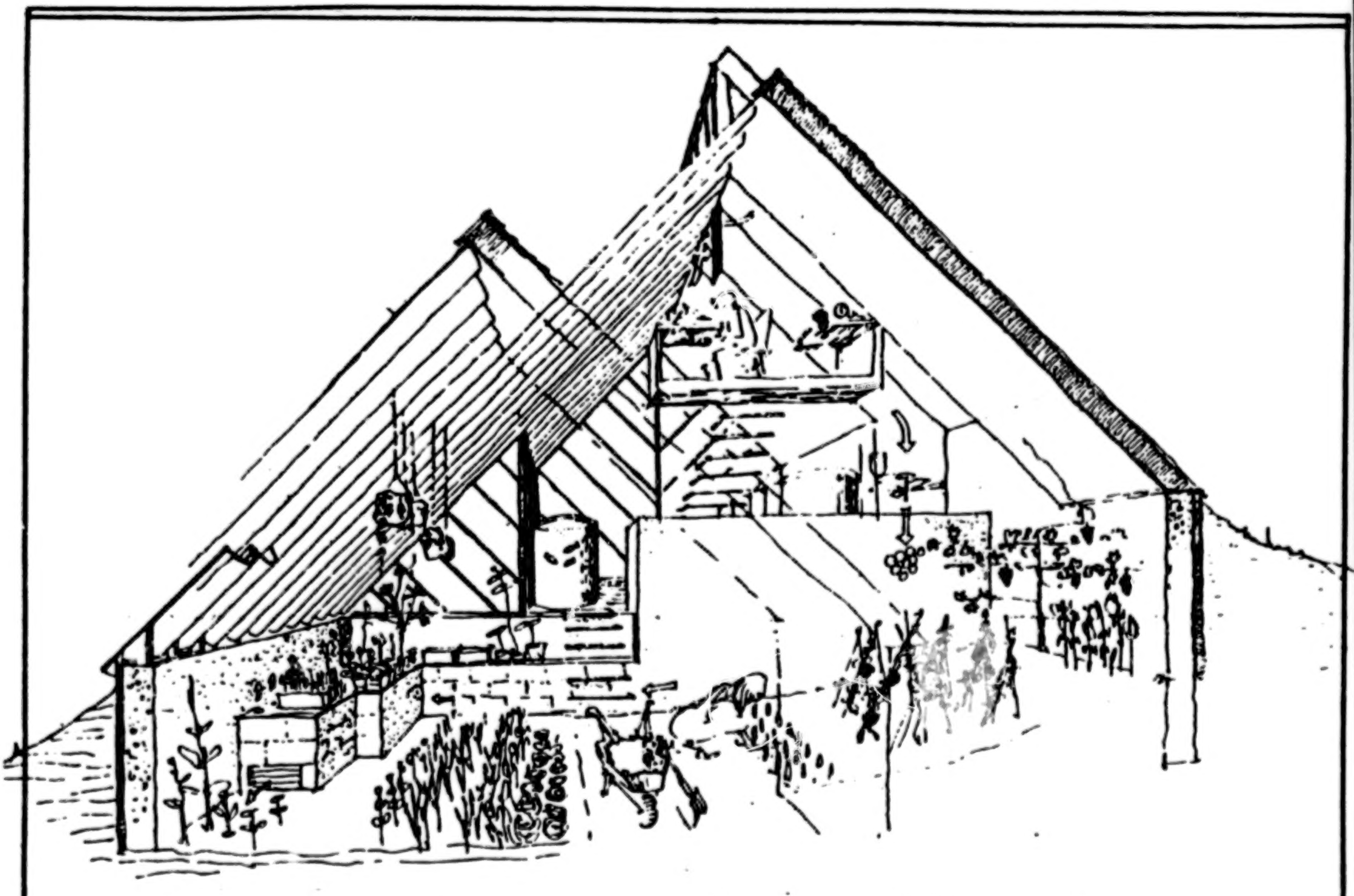

Figure 1. Sketch: Central Interior Zone

Rawitscher and Mayer[7] have calculated the number of kilocalories of energy to produce one gram of protein before processing or cooking in U.S. food production. We have adjusted their figures for protein lost in processing, and made similar calculations for our fish culture. Grains cost less (40 kilocalories), meats and luxury seafoods much more (400-1500 kilocalories). Solar pond aquaculture at New Alchemy requires from 84 to 140 kilocalories of energy to produce one gram of edible protein. These values bracket Israeli pond polyculture, eggs, and tuna fishing. Our figures include the capital of the aeration and support components, electricity for aeration (a major contributor that we intend to reduce in subsequent designs), feeds, and labor.[8] Note that the energy costs described here do not include storing or cooking costs. Nor are the protein outputs corrected for protein quality by NPU (net protein utilized) factors. Thus grains, with their long cooking times and low protein quality, may ultimately cost as much energetically as eggs and Ark-grown tilapia. Likewise, processing costs make canned tuna compare unfavorably to tilapia caught from the Ark and eaten fresh. These comparisons show that solar fish culture at New Alchemy Institute, although recently developed and not yet refined, is energetically sound.

Two years of research with the Cape Cod Ark have begun to vindicate the bioshelter concept. Ecological stability and disease- and pest-control have been achieved without the need for biocides. The food-raising environments have proven productive. The aquaculture has become the highest yielding standing body of water yet described. Valuable cash crops have been grown to maturity in winter. A number of food crop varieties adapted to the bioshelter solar environment have been identified. Looking toward the coming post-petroleum era, bioshelters may someday perform for society the role barns did in the pre-industrial and fossil fuel ages.

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[3] "Tomorrow is Our Permanent Address: An Ecological Design Science"; N. J. Todd and J. H. Todd. To be published by Harper and Rowe in 1979.

[4] To match note 5 values, cost is translated to 1967 dollars). If fabricated on site, the ponds cost much less than $150 @ in 1977 dollars.

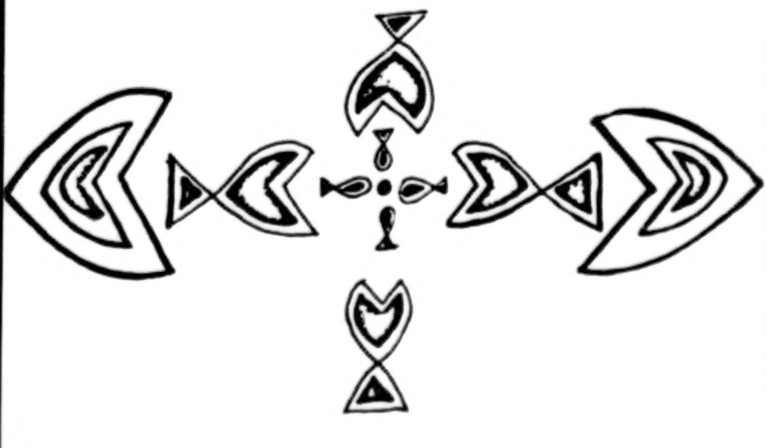
[5] Btu/$ figures are from Bullard, C. et al. 1975. Energy Flow Through the U.S. Economy. (wall chart). Center for Advanced Computation, University of Illinois at Urbana-Champaign.

[6] The output figures are conservative. Since diurnal ranges of 3.9° C have since been measured, 1200 x 10^6 cal/yr may prove more realistic.

[7] SCIENCE, 1977, Vol. 198, p. 262.

[8] The Energetics of Solar-Algae Pond Aquaculture, J. R. Wolfe. To be published in THE JOURNAL OF THE NEW ALCHEMISTS, Vol. 6.

John Todd is the President, and John Wolfe is the Ecosystem Modeller at the New Alchemy Institute. New Alchemy Institute is a small scientific research and educational organization with a supporting membership program, dedicated to the development of renewable resource-based and environmentally benign technologies to meet basic human needs. Requests about membership and publications can be sent to: The New Alchemists, P.O. Box 47, Woods Hole, Massachusetts 02543.



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New Alchemy Newsletter

Fall–Winter Issue **1978**

The Great Champagne Race

Last spring John Todd threw down the gauntlet: whoever grew the most fish, either a) fastest or b) most efficiently, in a solar-algae pond (the 5 ft. x 5 ft. fiberglass silos) would win a bottle of champagne and aquaculture fame. The loser would be shipped off to Bill McLarney's fish pond in Costa Rica to fight alligators.

The imminent arrival of two thousand hybrid tilapia fry (*T. honorum* males crossed with *T. mossambica* females) sparked frenzied construction activity. John, with engineering expertise from J. Baldwin, connected a pair of ponds with two large pipes. A simple, surprisingly effective pump, created by placing an air bubbler within one pipe, exchanged water between the ponds. Gary, Sarah and Hilde errected a chicken cage above a solar-algae pond, where the birds could nervously look out over the gardens from their perilous perch. Earle put a pond in the cattails depression, wrapping a vertical sheet of fiberglass in a spiral within the silo. A hose from the uphill goose pond trickled water into the center of the pond, where it flowed through the spiral maze to an outflow through at the perimeter. John Wolfe glued together plastic pipes, elbows and faucets into a gizmo purported to siphon a pond down 20% in a few seconds, and hammered together a fish cage of wood and plastic netting to protect tilapia fry from the maws of hungry bullheads.

Throughout the summer contestants were seen sprinkling secret potions into their ponds; whether acid/base buffers, guarded food formulae, or microbial aphrodisiacs, no one else then knew. Rumors of poisonings of one contestant's pond by a rival flared with the discovery of any fish acting strangely.

With the coming of cold autumn nights the single-walled ponds of the champagne racers cooled, while the double-walled solar courtyard ponds maintained steaming temperatures. The hard facts found when the ponds were drained are summarized in the table on this page.

Resident fish wizard Bill McLarney, who declined invitations to enter the race (one never sees the cagey, earthy codger around the solar-algae ponds with their slightly Star Trek flavor), was called upon to judge the results. Wolfe's pond was first declared winner of the no-holds-barred, all-out growth race. He was overheard bragging, "Just consistent feeding and bottom siphoning – management, you know." However, hours before we went to press, Ron Zweig pointed out the last solar courtyard ponds, just drained down, might have done better. Despite having *Tilapia aurea* rather than the faster growing tilapia hybrids, two ponds (*F* and *G*) squeeked ahead of Wolfe's record. The food conversion ratio of 2.4 was poor by NAI aquaculture standards, but it still surpassed the skyscraper chickens' ratio of 3.8. The new winner should be called the Butler / Doolittle / Engstrom / Goodwin / Janssen / Todd / Wolfe Wright / Zweig entry, better known as the NSF closed system project team.

The Barnhart/Gifford and the Bennet/Hirshhberg/Maingay entries exhibited clearly superior conversion efficiencies of external food to fish growth due to a heavy reliance on feeds within the ponds. Both ponds were manured, so bacteria and protozoans as well as algae probably acted as internal feeds.

CONTESTANT	FISH STOCK	TOTAL GROWTH (grams)	TIME PERIOD (days)	GROWTH RATE gm/day	GROWTH RATE lbs/yr	WATER CHANGE RATE (% week)	WATER VOLUME (gallons)	AERATION?	FEEDS DRY WT (grams)	FOOD CONVERSION RATIO
Pond "G" in Solar Courtyard	46 T. aurea	5639	106	53.2	42.8	20	640	YES	13680 trout chow	2.43
Wolfe's Polyculture	196 T. hybrid 17 Fathead Minnows 1 Brown Bullhead	4285	82	52.3	42.5	15	640	YES	4610 trout chow 150 insects	1.11
Todd's Twins	166 T. hybrid	2014	103	19.6	15.7	2	1200	YES	840 trout chow	.41
Bennet, Hirshberg, & Maingay's Chicken Skyscraper	125 T. hybrid 166	1040	76	13.7	11.0	0	640	NO	36 trout chow 60 worms	.092
Barnhart & Gifford's Clam Condominium	110 T. hybrid	1027	87	11.8	9.5	200	640	NO	23.4 worms/ grubs/ comfrey	.023

Though it appears from the table that the Clam Condominium wins hands down, the rules laid out in early summer specified no more than a twenty percent water change per week. Bill McLarney judged the Condominium should get a ten-fold handicap for its pint-per-minute flow rate, making the Chicken Skyscraper the winner of the efficiency race. Nevertheless, the Barnhart/Gifford pond demonstrates the potential of increased water change rates and internal surfaces.

Before sending John Todd off to Costa Rica, where he's longed to return since an idyllic stay in the early seventies, I should hasten to point out that the winners won by going to the extremes of either production *or* efficiency. From energetic, economic or ecological standpoints, it now seems that future winners should mix the two qualities, somewhat as John did, to get an elegant compromise.

Shortly after the foregoing article went to press we discovered that Barry Pierce of Goddard College had attained fish growth rates exceeding any at New Alchemy this summer. His Tilapia mossambica, Israeli carp and hybrid sunfish polyculture of 100 fish, initially 9.1 kgs, had a growth rate of 132 g/day or 106 lbs/year over an 82-day trial. He fed his fish 175 grams of insects per day; the food conversion ratio was 1.2. The insects appear to be his special ingredient. Astounded and excited by such results, we dutifully sent Barry our bottle of champagne.

Native North American Polyculture: A Beginning

by

Ron Zweig

One of the present efforts in aquaculture research at New Alchemy is to evaluate the usefulness of native North American organisms in intensive food production designs. Ultimately, this will lead to the development of polyculture strategies similar to those initially reported in China nearly twenty-five centuries ago (1). The Chinese methods have rendered the most efficient and productive designs for open ponds (2,3,4). Much fish culture research has attempted to emulate the Chinese work using many of the same species (4,5)--the herbivorous grass carp, *Ctenopharyngodon idellus*; the phytophagous silver carp, *Hypopthalmichthys molitrix*; the zooplankton feeding big head carp, *Aristichys nobilis*; and the detritus feeding common carp, *Cyprinus carpio*.

Clearly this strategy's use of different species to feed at the various trophic levels in an aquatic ecosystem is an excellent guide for fish culture. Moreover, to select species which feed low on the food chain is an important consideration. The ideal combination of organisms would not only follow these criteria but also contribute to the health of the pond through the management and control of biota within it. This is crucial to prevent severe eutrophic conditions from developing, frequently a result of intensive supplemental feeding.

The contention here is this: with the study of the natural history of aquatic organisms native to different regions of the world, a polyculture indigenous to those regions could be developed with similar efficiency to that initially established in the Far East.

Under intensive culture and feeding regimes, fish wastes released into pond water provide the nutrients necessary for dense phytoplankton blooms. If not controlled, these blooms can cause anoxic conditions threatening the life of the ecosystem. In early New Alchemy work (6), the phytophagous tilapia, *Sarothradon aureus*, native to africa was selected to keep the phytoplankton populations within safe densities, preventing algal senesence. The tilapia are tropical and known for their hardiness and ability to grow rapidly. In searching for a North American equivalent to this kind of organism, initially fresh water clams such as *Elliptio complanata* were considered. These clams do not grow very quickly, but would still be useful in managing the phytoplankton through filter feeding. Recently, Sterling Bunnell at Farallones Institute in California recognised that the Sacramento River Blackfish, *Orthodon microlepidotus*, a cyprinid native to that state, to be a potential replacement for the tilapia.

The blackfish has several good attributes for culture. Beyond being a plankton filter feeder, it has a wide temperature tolerance, from freezing to nearly 35°C. This fish inhabits shallow eutropic lakes, indicating that it can also withstand diurnal fluctuations in temperature, dissolved oxygen, and pH.(7) Sterling has found that they grow rapidly in captivity. They also have a flavor equivalent to that of the

the grass carp which is revered by the Chinese. Blackfish can be found for sale live in San Francisco markets.

We are presently evaluating the blackfish in the solar-algae ponds. It has demonstrated that it survives and grows within the conditions of these ponds. In one test, we combined it with several other fish species we have cultured to determine its compatibility with them. These include the tilapia, the yellow bullhead, bluegills, and a hybrid sunfish. All of these fish appear to coexist peacefully.

Bill McLarney and Jeff Parkin have been working with the omnivorous yellow bullhead, Ictalurus natalis, in an intensive cage culture experiment. They have found that this species is an excellent one to use under crowded conditions. It grows rapidly and remains free of disease It is another excellent candidate to be included in North American polyculture.

The yellow bullhead and blackfish combination would comprise a portion of a complete culture design. It is still necessary to include a detritivore and a herbivore to create an effective polyculture. The mirror carp, Cyprinus carpio var. specularus, is an edible fish extensively cultured in Israel. This fish is both a detritivore and a herbivore. It's swimming behavior also stirs sediments back into the pond water. Although it is not a native to North America, it should be similar to species here. Its equivalent needs to be identified. If readers are aware of such a species please contact us.

The spring of 1979 will be the beginning of the first culture trial using these species. They will be tested in a constructed,outdoor pond (20 X 10 X 4 ft.) containing 6000 gallons. An earlier experiment in one of the midge culture trenches with tilapia proved that this kind of shallow pond could be a viable, productive one (8). One hundred individuals from each species will be stocked.. The blackfish will function as the plankton feeder, and the yellow bullhead will be fed a high protein diet including Chironimid larvae. The mirror carp, unless a similar native is located soon, will be used to feed upon and recycle the wastes from the other species in this trial. The carp will also be fed fresh comfrey, which is high in protein and B vitamins. These plants as well as the midges will be grown adjacent to the pond. Also, Susan Ervin and I will be coupling this culture system with hydroponics as an auxillary recirculating water purification component.

One of the best aspects of this design is that these temperate fish should grow efficiently outdoors for up to six months per year in the Cape Cod environment. All of these fishes tolerate the anticipated temperature and water chemistry fluctuations. We hope to raise fingerling-size fish to edible size (250 grams) within a single growing season.

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The New Alchemists

To Restore The Lands, Protect The Seas, And Inform The Earth's Stewards

AQUACULTURE AND ITS PLACE IN SOLAR ARCHITECTURE

by

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Abstract

Solar-algae ponds (translucent fiberglass cylinders five feet in diameter and height) are efficient passive solar collectors and fish production components in greenhouse structures. Several outdoor reflective designs have been evaluated for the maximization of light entering the ponds. The indoor thermal energetics of the ponds demonstrate that for every calorie of energy used in their manufacture an equivalent of five calories will be returned in the form of heat during their expected twenty year lifetime. The ponds' phytoplankton-based aquaculture has proven to be a stable, productive ecosystem. Between ten and twenty times greater fish productivity of any previously described standing body of water has been achieved using species feeding low in the food chain. The algal cells in the water column are useful (1) as a feed for phytophagous food organisms, (2) in the oxygenation of the water through photosynthesis, (3) as micro-heat exchangers absorbing solar energy, and (4) in the purification of the water through directly metabolizing toxic fish wastes.

The water chemistry and phytoplankton population dynamics have been monitored and recorded through several production trials. Different feeds have been evaluated regarding their impact upon the nature of these aquatic ecosystems and the growth of the tilapia, Sarotherodon aureus, within them. This data is being used toward the development of an ecological model to assist in optimizing the use of the solar-algae ponds and the development of a simple guide for fish culture. It has been found that under intensive supplementary feeding regimes to maximize fish growth, the ponds are loaded with nutrients beyond what can be assimilated by the phytoplankton. Several of these compounds inhibit fish growth, but nurture plants. A strategy using this fertile pond water to irrigate vegetables in exchange for a fresh supply benefits both production schemes through the efficent double use of a single water and nutrient source.

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